Utilising linkography to understand the cognitive mechanisms of technology learners during the design process

by

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Submitted in partial fulfilment of the requirements for the degree

Philosophiae Doctor

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DECLARATION OF ORIGINALITY

I declare that the thesis titled "**Utilising linkography to understand the cognitive mechanisms of technology learners during the design process"** which I hereby submit for the degree Philosophiae Doctor at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

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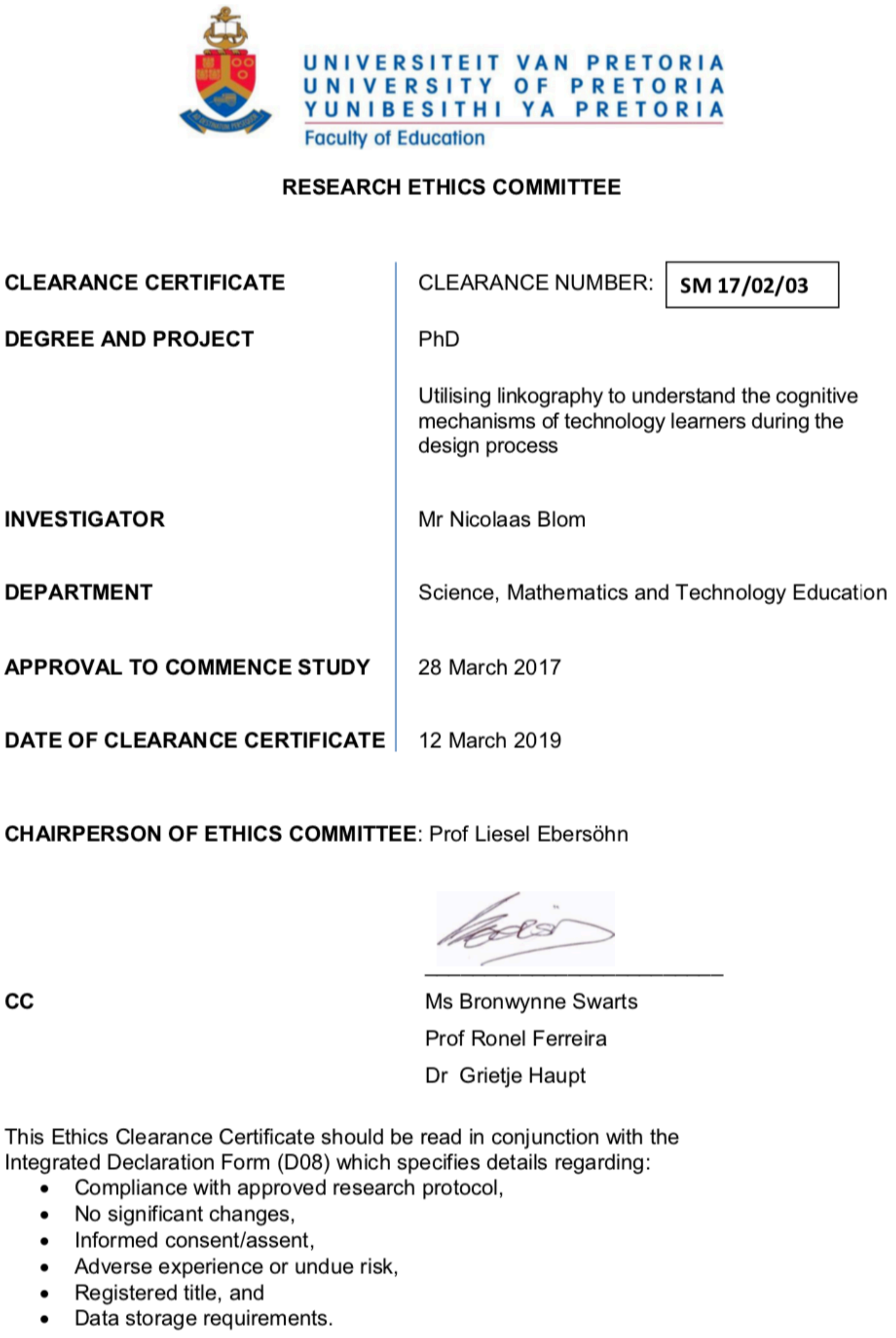

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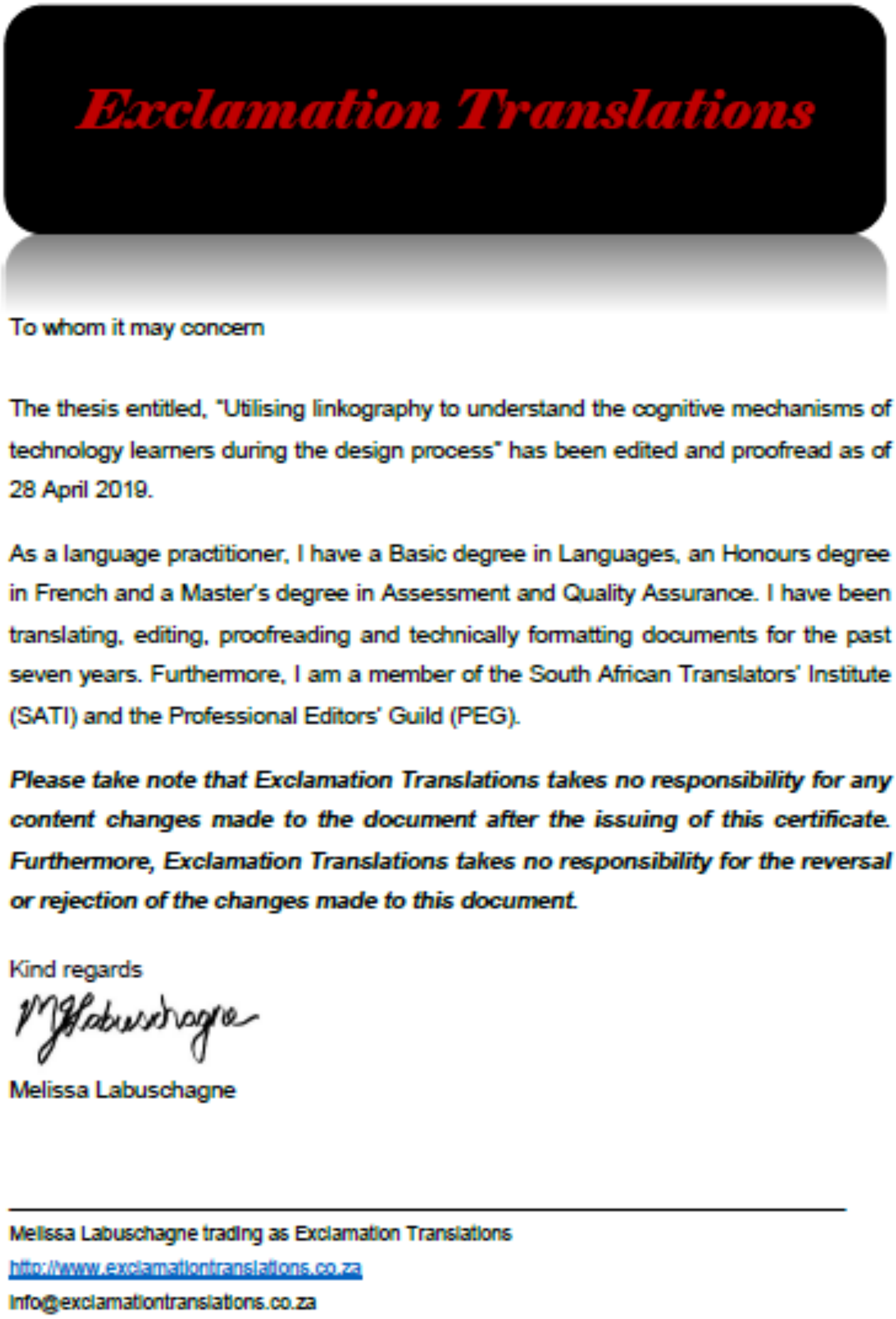

Exclamation Translations

To whom it may concern

The thesis entitled, "Utilising linkography to understand the cognitive mechanisms of technology learners during the design process" has been edited and proofread as of 28 April 2019.

As a language practitioner, I have a Basic degree in Languages, an Honours degree in French and a Master's degree in Assessment and Quality Assurance. I have been translating, editing, proofreading and technically formatting documents for the past seven years. Furthermore, I am a member of the South African Translators' Institute (SATI) and the Professional Editors' Guild (PEG).

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ABSTRACT

The 21st century is marked by an increase in information sources available to designers when solving design problems. Current design thinking procedures and theoretical frameworks do not, however, elucidate how designers rely on a variety of social, conceptual and physical information sources when designing. As such, ongoing research is required to not only understand how designers interact with information sources, but also to find suitable methodologies for investigating such interactions.

The purpose of this study was threefold. Theoretically, I aimed to explore and describe how Grade 8 learners' thoughts can develop during the design process as a result of their interactions with social, conceptual and physical structures during a STEM task. Methodologically, I attempted to demonstrate the implementation of linkography as an emerging methodological strategy when studying learners' thought processes. Finally, I developed a model of learners' extended design cognition during the early phases of the design process that may hold practical application value for pre-service and in-service teachers.

My study is embedded in Extended Design Cognition and Activity Systems Theory. I implemented a mixed methods design, following a critical realist approach. I conveniently sampled three medium-resourced schools and purposefully selected nine Grade 8 participants. Verbal (spoken and written) and visual (sketches, 3D models and gestures) data were generated and documented by means of Think Aloud Protocol methodology, and analysed quantitatively and qualitatively, utilising linkography.

This study makes an ontological contribution in terms of the basic structures, mechanisms and events underpinning learners' design processes. Findings indicate that learners will synthesise their understanding of a design problem and possible solutions by way of incremental forward and backward design moves, while building on their own and one another's thoughts during collaborative designing.

Although the participants engaged actively with technological knowledge, they rarely used scientific knowledge. The physical environment however played a vital role in scaffolding and supporting their design processes by means of perception-action cycles.

KEY CONCEPTS

- Activity Systems Theory
- Critical realism
- Design cognition
- Ecological Psychology
- Extended cognition
- Linkography
- Novice designers
- STEM education
- Technology Education
- Think aloud protocol study (TAPS)

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CHAPTER 1

GENERAL ORIENTATION AND INTRODUCTION

1.1 INTRODUCTION AND BACKGROUND TO THE STUDY

Schooling worldwide adjusts itself according to the dynamic landscape and movement in the political, social, and economic milieus in which countries are situated. As a result, in the early 1990s, several countries started focusing on the implementation of STEM in schools (Williams, 2011; Sanders, 2009). STEM is an acronym for the disciplines of science, technology, engineering and mathematics. As STEM was initially introduced to support economic dominance, STEM initiatives have been funded by government authorities and promoted by politicians worldwide as a pathway to vocational and economic goals (Williams, 2011). Furthermore, STEM initiatives have been encouraged in many countries as a means to avoid economic recessions, such as the Global Financial Crisis (Williams, 2011), even though such campaigns are typically based on assumptions and speculation by political figures (Williams, 2011).

A decline in STEM workforces has also increased politicians', academics' and professionals' focus on promoting STEM-based careers (Kuenzi, 2008; Williams, 2011). While politicians reason that a STEM workforce could contribute to maintaining global economic dominance, academics and professionals in the four key discipline areas of science, technology, engineering, and mathematics are primarily concerned about increasing student enrolments in existing STEM programmes (Sanders, 2009). It follows that the rationale for initial STEM initiatives were seemingly not supported by pedagogical aims and objectives, but rather entailed teachers being tasked to merely implement STEM curricula in both primary and secondary schools. However, several challenges have prevented the effective instruction of STEM subjects in various contexts. For example, 'engineering' is not included in the school curricula of either primary or secondary schools, nor are pre-service science and mathematics teachers trained in engineering methodologies (Blackley & Howell, 2015). Furthermore, differing interpretations of the meaning of 'technology' have resulted in confusion and frustration amongst teachers (Williams, 2011). Such challenges related to the understanding and implementation of ‘engineering’ and ‘technology’, have in turn resulted in three questionable implementation approaches to STEM.

First, some teachers have continued to focus on their traditional ways of teaching science and mathematics, thereby ignoring certain technology and engineering components, which has resulted in a view that technology and engineering are subordinate to science and mathematics (Asunda, 2012; Kelley & Knowles, 2016). A possible reason for this ‘SteM’ approach relates to teachers’ lack of prior training and limited availability of curriculum documents to guide them in implementing technology and engineering in the classroom. The second questionable approach to the implementation of STEM is based on the ongoing debate regarding the meaning of the concept ‘technology’. Some teachers maintain that technology refers to educational technology devices with which teachers can support the teaching and learning process; while others merely view technology as artefacts and devices used by human beings for technological goals, or simply as a body of knowledge and skills.

Third, in vocational settings, a ‘sTEm’ approach is typically preferred (Breiner, Harkness, Johnson, & Koehler, 2012). Vocational settings are often driven by political agendas with the purpose of increasing the number and retention of highly capable professionals in the engineering and technology fields. This view supports a sTEm enactment, implying a discord between what schools have been enacting, and what occurs in vocational settings. At the heart of these three approaches lies the challenge of understanding what an integrated STEM education curriculum may look like, and how it can be efficiently enacted in the classroom. Despite teachers being tasked to enact integrated STEM education, the goal of an integrated STEM curriculum cannot be addressed without the necessary prior training of those who need to implement the task (Blackley & Howell, 2015).

Based on the context provided in this section, I was motivated to conduct the current study. More specifically, I undertook an investigation that focused on introducing real-world integrated STEM activities during children’s schooling years that may potentially demonstrate the value of such an approach. Limited available research on the way in which learners engage in integrated STEM activities, as well as current debates and concerns about the situation in international and national STEM education, further motivated me to conduct this study.

1.1.1 Towards a pedagogy for integrated STEM education

In an attempt to improve the efficient implementation of STEM, educational communities have challenged political views on STEM implementation through a pedagogical lens (Blackley & Howell, 2015). As a result, 'STEM' was changed to 'STEM education' in the 2000s, allowing teachers and curriculum developers to take over the ownership thereof from politicians, thereby highlighting their role in implementing STEM in the educational context (Blackley & Howell, 2015; Ritz & Fan, 2014). However, at the time, limited meaningful modifications to teaching practices or improvement in student learning achievement prevailed. Following the change to 'STEM education', most practices remained in the form of informal activities after school, or extension programmes that were additional yet not always complementary to routine school activities. Furthermore, these activities were typically only open to self-nominated learners or academically high-performing invitees. Despite the high levels of energy and money being invested in STEM education, little measurable outcomes and successes could be observed in achievement scores and supply for the STEM workforce (Blackley & Howell, 2015).

Two primary reasons for the limited success of initial STEM education as a pedagogical approach continued to be the lack of curriculum structure, and the limited skills level and/or professional preparation of teachers. These two reasons subsequently led to a crisis point in the 2000s, with teachers and curriculum developers starting to take ownership of STEM education, governments still investing large amounts of money in STEM education initiatives, but with economic goals not being addressed and a continued shortage of trained STEM workers. From a pedagogical point of view, this period in STEM education remained to be characterised by limited consensus about what STEM education entailed and how it could be taught (Asunda, 2012; English, 2016; Kelley & Knowles, 2016).

As such, a change in conceptualising STEM education became necessary. As a result, a significant re-naming of 'STEM education' to 'integrated STEM education' occurred in 2007. This renaming was based on growing appreciation for the integration of the four disciplines (science, technology, engineering, and mathematics) in environments outside the school context. As a result, integrated STEM education implies a curriculum that is based on the idea of educating learners in the four disciplines of science, technology, engineering and mathematics in an integrated way by following an interdisciplinary approach (English, 2016). In terms of current STEM curricula, the design process typically drives learners' learning experiences, with knowledge and skills from science, technology and mathematics being applied to real-world problems (Kelley & Knowles, 2016).

Integrated STEM education has become increasingly important since its introduction (English, 2016; Kelley & Knowles, 2016), based on contemporary times and trends. More specifically, to live, learn and work efficiently in an increasingly complex society requires of lifelong learners the development of 21^{st} century skills, such as complex problem solving of real-life problems, decision making, knowledge creation, collaboration and being capable users of technology (Pink, 2010; Wagner, 2010). As such, scientific, technological, engineering and mathematical literacy seems to be an important requirement for modern times (Kelley & Knowles, 2016).

To this end, governments of developed and developing countries regard such literacies as an important investment in developing 21^{st} century skills among learners (Daramola, 2015; Matthews, Ryan-Collins, Wells, Sillem, & Wright, 2012; UNESCO, 2010). In this regard, Kelley and Knowles (2016) argue that scientific, technological, engineering and mathematical literacy can be viewed as a priority in formal education on an international level. Globally, integrated STEM education is thus viewed as a means of not only improving education, but also of improving science, mathematics and technology outcomes in general (Asunda, 2012; English, 2016; Kelley & Knowles, 2016). This possibility relates to the aim of integrated STEM education to produce scientifically, technologically, engineering and mathematically literate citizens, possessing the necessary skills required in the 21^{st} century (English, 2016).

1.1.2 Challenges related to STEM education in South Africa

In line with the focus on integrated STEM education worldwide, the South African Department of Basic Education claims to (GCIS, 2015, p. 56):

> *"develop, maintain and support a South African school education system for the 21st century in which all citizens have access to lifelong learning, as well as education and training, which will, in turn, contribute towards improving the quality of life and building a peaceful, prosperous and democratic South Africa".*

However, the South African education sector is currently viewed as being in a crisis (Fleisch, 2008; Spaull, 2013; Stott, Mofu, & Ndongeni, 2017). According to the *World Economic Forum Global Competitiveness Report 2017–2018*, South Africa was at that stage ranked last out of 140 countries across the world for the quality of its science and mathematics education (World Economic Forum, 2018). Furthermore, the *Trends in International Mathematics and Science Study (TIMSS)* results indicate that South African learners underperform in mathematics and science education when compared to their international peers (Spaull, 2013). Similarly, the *Annual National Assessments (ANAs)* confirm that a majority of South African learners underperform (Van der Berg, 2015).

Science and mathematics are generally viewed as the gateway subjects for STEM-related careers. This view emphasises the need and responsibility of the South African educational system to produce learners that are capable of passing mathematics and science at Grade 12 level. Despite the need to produce scientific and mathematically literate learners, a large-scaled research project (Spaull, 2013) indicates that the South African Department of Education is still failing to produce sufficient numbers of learners passing these subjects at the Grade 12 level. In further support, a recent study by Coetzee and Mammen (2017) indicates that entry level students in engineering often lack the necessary numeracy skills to excel in their courses. As a result, South Africa currently experiences a shortage of skilled scientists and engineers who can meet the workforce requirements of industry, commerce, health and education (Spaull, 2013). This shortage of scientists and engineers is reiterated by Kramer, Goldberger, Tallant, and Lund (2014) in the *Global STEM Paradox report*, where the authors state that Sub-Saharan Africa requires 2.5 million more engineers in order to address the continent’s development challenges, these being poverty, hunger, disease and overreliance on foreign aid. In comparison to the international norm of one engineer per 40 people, South Africa lags far behind with one engineer per 2600 people (ECSA, 2015).

At present, it is still not clear how design problem solving can be taught in an effective way to learners who aspire to become engineers. A key feature of effective designing is collaborative decision making and ill-structured problem solving (Jackson, Mentzer & Zissimopoulos, 2015; Wendell, Wright, & Paugh, 2017), which highlights that when designing, learners need to access and use a variety of information sources in order to select design objectives; identify design constraints; decide on alternative solutions; choose the shape, structure and appearance of a design solution; and decide about the technical feasibility of solutions (Haupt, 2018b; Jackson et al., 2015; Trebell, 2009). However, questions about types of information sources, tools, classroom rules, communities, and division of labour – beyond prescriptive curriculum materials – remain (Wendell et al., 2017).

Currently, teachers often implement project-based learning as a pedagogical approach to facilitate learning in integrated STEM education (Capraro, Whitfield, Etchells, & Capraro, 2016; Capraro, Capraro, & Morgan, 2013). This is done without empirical evidence of how learners cognitively engage in STEM activities. One of the contentions in this thesis is that in the rush to adopt project-based methodologies for integrated STEM education, teachers may be missing the role that disciplinary knowledge, which is embedded in science, mathematics and technology, as well as the social and physical environment, play in supporting learners' design cognition. Against the background of project-based learning generally being regarded as an effective approach to instruction in STEM education, while also considering the related challenges, I set out to explore how learners may engage in an integrated STEM activity.

The purpose of this study was therefore to explore the internal and external cognitive mechanisms underlying design problem solving events in the early phases of Grade 8 learners' design processes. More specifically, I wanted to understand how learners' interactions with social, conceptual and physical structures engendered their design cognition. My decision to involve Grade 8 learners as participants is based on the curriculum of this particular year in the South African school context, where learners are taken to have developed conceptual understanding related to heat transfer, measurement and the properties of materials. Such conceptual understanding was important for the participants in this study for them to be able to engage in the design task that I gave them and to design a biodegradable heat container. Insight into the way that cognitive events may emerge as a result of interaction between learners, and internal and external cognitive mechanisms, may ultimately contribute, not only to theoretical knowledge, but also to current pedagogical practices within the field of integrated STEM activities.

1.2 RATIONALE FOR FOCUSING ON LEARNERS' COGNITIVE PROCESSES DURING THE EARLY PHASES OF AN INTEGRATED STEM ACTIVITY

This study stems from the need for ongoing empirical research on integrated STEM education (Fan & Yu, 2017; Hernandez et al., 2014; Strimel & Grubbs, 2016). In particular, I decided to focus on the social, cognitive and physical structures and mechanisms underlying learners' design problem solving events during integrated STEM activities in an attempt to contribute to the field theoretically, methodologically and to professional practice. By undertaking this study, I thus aimed to add to the debate between teachers and researchers about what to look for and what to support during learners' design processes. Although research on designing in school contexts has gained traction as an emerging topic of interest, research on design cognition, and practices in public school settings specifically, remains limited (Haupt, 2018a; Strimel, Kim, Bartholomew & Cantu, 2018; Sung & Kelley, 2018). As such, ongoing research is important to understand how learners' design cognition occurs as a result of their interactions with social, conceptual and physical structures in the learning environment.

1.2.1 Potential theoretical contribution of the study

Several scholars (Campbell & Jobling, 2014; English, 2016; Kelley & Knowles, 2016) concur that integrated STEM education is a potentially effective instructional method for fostering critical thinking, problem solving and decision-making skills. However, empirical evidence to support the cognitive benefits of integrated STEM education seems limited (Asunda, 2012; English, 2016; Williams, 2011). In addition, several limitations in the existing literature compromise the universal acceptance of integrated STEM as an appropriate framework. Examples of such limitations are impoverished descriptions of research interventions, a lack of common terminology and theoretical frameworks, and limited evidence on the benefits of interdisciplinary learning (National Academy of Engineering, 2014).

Based on a review of the implications of psychology and neuroscience for STEM learning, Howard-Jones and Jay (2014) highlight the importance of researchers developing methods for research that can combine concepts and insights at the intersection of the psychology and educational domains (Jay, 2013; Jorg, Davis, & Nickmans, 2007). According to these authors, potential research findings will however remain inaccessible as long as traditional disciplinary boundaries can be observed, and the dynamic interactions between the social, cognitive and physical environment are ignored (Howard-Jones & Jay, 2014). It follows that a deeper understanding of the cognitive mechanisms underlying learners' design processes during integrated STEM activities may result in teachers being better informed about the strategies that are suitable for supporting learners' design problem solving activities.

By investigating these underlying cognitive mechanisms, the findings of the current study may potentially contribute to the ontological understanding of learners' design cognition. As such, the philosophical concept 'ontology', which implies the study of the nature of existing entities – physical or abstract (Hofweber 2014), forms a focal point in this study. As such, the potential theoretical contribution of this study entails increased understanding of the nature and types of thoughts underlying learners' design processes, and how learners' interactions with social, conceptual and physical structures may engender these thoughts. As an outcome, this study suggests a novel training model (refer to Chapter 6) through which learners' design problem solving during STEM activities can be conceptualised.

Theoretically, the findings of this study may thus add to existing literature on the way in which learners design during STEM activities. More specifically, I hope to contribute to the Extended Design Cognition Theory of Haupt (2015) concerning the way in which learners may engage in design problem solving tasks while collaboratively using disciplinary knowledge from STEM subjects, and information in the external environment.

1.2.2 Potential methodological contribution of this study

Verbal protocols have been used as a primary method of inquiry for the last 40 years when studying the thought processes of designers. In technology education, verbal protocols have been specifically utilised to explore students' processes of design in terms of their design procedures (Mentzer, 2014; Welch & Lim, 2000), mental processes employed (Kelley & Sung, 2017; Strimel et al., 2018), different values used

(Trimingham, 2008), and the different cognitive design styles and reasoning that students may exhibit (Lammi & Becker, 2013; Wells et al., 2016), to mention but a few. By using verbal protocol methodology, researchers can collect systematic evidence of designers' incremental thought processes and behaviour as they occur during a design task (Grubbs, Strimel & Kim, 2018; Sung & Kelley, 2018). When carrying out this research, captured verbal reports and behaviours were subsequently transcribed and coded, with analysis involving the studying of the design process in small units. Although verbal reports can never be a complete representation of students' thought processes, they can provide some access to the thinking involved in designing, which would otherwise not necessarily be accessible (Goldschmidt, 2014).

Specific coding frameworks are typically utilised to analyse the verbal protocols of technology education students (Grubbs et al., 2018). Some frameworks emphasise the procedural nature of designing, while others have a cognitive science foundation and reflect an ontological approach to analysing students' cognition. However, none of the frameworks that Grubbs et al. (2018) identified as often-implemented provide a way to characterise students' developing thoughts during designing. Furthermore, existing frameworks do not always allow researchers to investigate students' interactions within the physical environment, which may give rise to their thoughts during designing. On the contrary, it seems as if the existing frameworks were developed predominantly from internalist cognitive science theories and often neglect the situated nature of students' thought processes. Thus, this study may add to current methodologies for studying learners' design cognition by introducing linkography as a novel method to study learners' moment-to-moment thought generation processes.

1.2.3 Practical contribution to integrated STEM education practice

Currently, there is a paucity of existing research that focuses on the naturalistic way in which learners analyse ill-structured problems, select their design objectives, propose new design ideas, compare existing design solutions, evaluate their ideas and make decisions during designing (Haupt, 2015; Jonassen, 2011). Limited empirical evidence or pedagogical support for guiding and fostering learners' design problem solving activities, however, exists. More specifically, despite global support for an integrated STEM movement at primary and secondary school level (Fan & Yu, 2017; Ritz & Fan, 2014; Xie, 2014), little is known about the way in which integrated

STEM can be taught. Although several claims have been made about the value and effectiveness of integrated STEM education, the way in which integrated STEM environments can enhance leaners' problem solving requires further research. In particular, the way in which learners may solve integrated STEM problems by utilising disciplinary knowledge from science, mathematics and technology remains an emerging area of research.

Ongoing research in this field is therefore required by practitioners in order for them to propose and develop effective pedagogical guidelines that may foster ill-structured problem solving skills amongst learners. Although integrated STEM education can be seen as a way of engaging learners with STEM content, deeper insight is required in terms of how learners engage, why certain efforts can be regarded as effective, and how learning processes can be recreated that will enhance ill-structured problem solving skills.

Another limitation indicated by the existing literature in the field of STEM education practice relates to the way in which groups of learners generally approach design problems (Jonassen, 2011) and furthermore, how collective disciplinary knowledge may enhance design problem solving (Gweon, Jun, Finger, & Rosé, 2017; Mentzer, 2014; Wendell et al., 2017). Existing studies on individual and team design decision making (Barlex, 2006; Jackson et al., 2015; Mettas & Norman, 2011; Thorsteinsson & Olafsson, 2011) typically focus on the importance of decision making as a fundamental design skill or on the factors involved in decision making, but seldom explore what learners actually do with prior disciplinary knowledge when solving design problems. Existing studies furthermore do not focus on the relationship between microscopic interactions involving internal and external cognitive mechanisms, and the macroscopic design problem solving process. To this end, this study may contribute to the knowledge and skills based on integrated STEM education practice. More precisely, it holds the potential to inform pre-service and in-service training on planning design tasks that considers the effective use of social, conceptual and physical resources during learners' design processes. In addition, the current study might make pre-service and in-service teachers aware of the nature of learners' thought processes in order for them to better facilitate the effectiveness thereof.

1.3 PURPOSE AND AIMS OF THE STUDY

In line with the potential contribution areas of this study, the purpose of this study was threefold. Theoretically, the purpose of the study was to explore and describe how Grade 8 learners' thoughts can develop during the design process as a result of their moment-to-moment interactions with social, conceptual and physical structures during a STEM task. By doing this, I furthermore aimed to explain how such interactions can give rise to emergent design thinking. To this end, I explored the various social, conceptual and physical structures considered by the participants to solve their design problems throughout this study. The findings of the study may, as a result, subsequently inform literature related to the influence of using internal (conceptual) and external (social and physical) resources in the early phases of the design process.

In terms of the methodological purpose of the study, I aimed to explore and demonstrate the implementation of linkography as an emerging methodological strategy when studying children's thought processes. Linkography was developed within the context of professional design studies in the 1990s, yet it has not been used in a school context, neither has it involved learners as participants. As such, in undertaking this study, I attempted to foreground the use of linkography as an emerging research method.

Finally, I was guided by a purpose related to integrated STEM education practice. To this end, I aimed to develop a model of learners' extended design cognition during the early phases of the design process that may potentially be used during the pre-service and in-service training of technology teachers. This model can perhaps raise teachers' awareness of the nature of learners' thought processes as the learners interact with various internal and external resources during the early phases of the design process.

In order to achieve these purposes, I involved groups of Grade 8 participants from three different medium-resourced schools, giving each group an open-ended STEM design task to complete. This task had the function of eliciting the participants' design cognition, which could generate data for me to document. I then analysed the documented data by using linkography in order to firstly explore and describe how learners' thought processes developed incrementally while they were interacting with social, conceptual and physical structures during designing. Secondly, I did this to describe the use of linkography; and thirdly, to subsequently make recommendations based on the findings I obtained.

In my endeavour to keep this study as natural as possible, I investigated how triads of novice designers approached a specific STEM task. Furthermore, even though Think Aloud Protocol Studies (TAPS) are often utilised for data generation without including the physical environment as a unit of analysis when reporting on the characteristics of the design problem solving process, I conducted research in this field while implementing an innovative approach to researching novice design behaviour in controlled naturalistic environments. In addition, by using linkography to analyse the moment-to-moment thought processes of the participants, I aimed to demonstrate how the emergent thoughts of the learners were instantiated while learners interacted with internal and external resources.

1.4 RESEARCH QUESTIONS

In accordance with the purpose statement, this study was guided by the following two central research questions:

1. How can insight into learners' interactions with social, conceptual and physical structures during designing inform existing theory in design cognition? *(Theoretical question)*

2. How can the implementation of linkography inform the development of methodologies suitable to investigate learners' design cognition? *(Methodological question)*

In order to address my primary research questions, I was guided by the following secondary questions:

- How did the social interactions of the learners shape the emergence of their design processes?
- How did the learners' interactions with conceptual structures contribute to the emergence of their design processes?
- How did the learners' interactions with physical structures facilitate the emergence of their design processes?

- How did the learners interactively use conceptual and physical structures during their design processes?
- To what extent can linkography be utilised to understand technology learners' thought generation during designing?

1.5 WORKING ASSUMPTIONS

Based on the literature I consulted in the fields of Extended Design Cognition Theory (Haupt, 2015), Activity Systems Theory (Engeström, 2015) and linkography (Goldschmidt, 2014) as methodological strategy, I conducted this study assuming that:

- Designing is a complex cognitive activity involving a range of cognitive processes.
- Design problems are unique and differ from other problem types in terms of the way in which they are structured and defined, which may in turn influence the way that learners think.
- As cognition is viewed as both internal and external, thinking implies the processing of internal information, as well as the direct perception of information from the physical environment.
- Learners' internal thought processes in the early phases of designing can be investigated by studying their external representations.
- Linkography can provide both a qualitative and quantitative avenue to understand the way in which design ideas are synthesised from connected backward and forward linking thoughts.

1.6 CLARIFICATION OF KEY CONCEPTS

In this section, I explain the key concepts that underpinned this study within the context of my focus area.

1.6.1 Linkography

Linkography is a verbal protocol analysis method that allows researchers to capture the structure of emerging thoughts as they occur sequentially during a design process (Gero & Kan, 2017; Goldschmidt, 2014). Linkography provides a visual representation of learners' processes of design, which can be qualitatively and quantitatively analysed. In order to analyse how learners design, verbal utterances are segmented into design moves.

According to Goldschmidt (2014, p. 30) a design move is “a small unit of verbalization lasting a few seconds” and refers to “an act, an operation, that transforms the design situation somewhat relative to the state it was in before that move” (Ibid. p. 42). A design move sometimes underpins a decision, or a tentative assertion; yet it may also entail a question regarding an aspect of an emerging design, a side comment, or a request for information (Goldschmidt, 2013). A design move is known as the smallest perceivable and coherent unit of operation that can be made during designing. Goldschmidt (2013) notes that design moves can thus consist of utterances, ranging from a few words to a few sentences. In essence, design moves are microscopic steps and are discernible from their contents.

For this study, the unit of analysis consisted of the verbal utterances of groups of participants that I segmented into design moves. Following this segmentation, I was able to trace the incremental development of the participants’ thoughts from the moment they received the STEM task, to the moment they chose a preliminary design solution. Insight into the design moves produced by the participants formed the backbone of my understanding of the social, conceptual and physical structures underlying the participants’ thoughts during designing.

In characterising design moves, Goldschimdt (2014) identifies four different types, consisting of orphan design moves, unidirectional design moves, bidirectional design moves and critical moves. This classification allowed me to study the different types of thoughts that were generated as a result of the participants’ interactions with social, conceptual and physical structures. I elaborate on the design moves in Chapter 3.

1.6.2 Cognitive mechanisms

When I studied the participants’ cognitive processes, I paid specific attention to the underlying cognitive mechanisms that could enable learners’ design problem solving. The term ‘mechanism’ emerged during the 17th century and is derived from the Greek word ‘*mekhane*’ and the Latin term ‘*mechanismus*’ which means ‘to have power’ or ‘that which enables’ (Craver & Tabery, 2017; Dijksterhuis, 1961[1]). In line with Descartes (1998), who espoused mechanical philosophy and understood mechanisms as the basic building blocks of the physical environment, I refer to cognitive mechanisms in this study as the basic psychological and physical building blocks of participants’ design problem solving processes. In his seminal work on critical realism, Bhaskar (1975) describes mechanisms as ‘ways of acting of things’. Furthermore, mechanisms exist independent of existing knowledge on them and whether or not they are enacted. For example, from an extended cognition perspective, cognitive agents possess cognitive capacities, even though these cognitive capacities are not always instantiated (Menary, 2007). For this study, I was interested to uncover the nature of the mechanisms that facilitated the interaction between social, conceptual and physical structures, which in turn gave rise to new design moves.

From a critical realist perspective (my selected epistemological paradigm – refer to Section 1.8.1), structures are one of the basic ontological elements through which reality can be known (Bhaskar, 1998; Bygstad, Munkvold & Volkoff, 2016; Wynn & Williams, 2012). Structures can thus be defined as a “set of internally related objects or practices” (Sayer, 1992, p. 92). As such, structures constitute the objects of knowledge or the entities under study (Danermark et al., 2002), which can be social, conceptual or physical in nature. From a Systems Theory perspective, structures may contain component structures, or may themselves be part of a larger structure (Easton, 2010). In this study, I was interested in the participants’ interactions with social, conceptual and physical structures within the STEM task environment in an attempt to understand how learners’ design problem solving events emerge.

For the purpose of the current study, social structures included the participants themselves and the way in which they interacted with each other. Conceptual structures consisted of any internal source of information stored in their long term memory, for example, STEM knowledge or prior experiences. Finally, physical structures refer to any external tool such as rulers, kitchen scales, cardboard material

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[1] Throughout my thesis I rely on some sources older than 30 years. Even though I realise that these are dated sources, I regard them as seminal sources and therefore as valuable resources.

and scissors; or information sources, including photographs, sketches and 3D models that the participants interacted with during designing to develop their thinking processes.

1.6.3 Technology learners

According to the South African Schools Act (1996), a learner can be defined as any person receiving education or any person who is obliged to receive education. For the purpose of this study, technology learners refer to Grade 8 learners who have technology as a compulsory school subject. In South Africa, technology is compulsory for all Grade 7 to Grade 9 learners. These learners are typically between the ages of 13 and 17.

Technology as a subject involves four content areas, being structures; processing; mechanical systems and control; and electrical systems and control. As a school subject, Technology will provide learners with opportunities to use newly acquired knowledge, and meet people’s needs and wants by developing practical solutions, while considering the social and physical environments (Department of Basic Education, 2011). For my study, I was specifically interested in understanding the design processes of learners’ while they solved a given real-world problem.

1.6.4 Design process

A design process can be described as an open-ended problem solving process that consists of various phases (Dym, Little & Orwin, 2014; Goel, 2014; Jonassen, 2011). These phases typically involve designers aiming to understand a problem, find suitable solutions, and realise solutions, while continually evaluating the process and solution (Dym et al., 2014; Goel, 2014; Jonassen, 2011). In this study, I decided to limit my investigation to the early phases of learners’ design processes. Accordingly, I only studied the way in which the learners understood the design problem, and how they generated preliminary design solutions to address the problem.

Several authors (Goel, 1995; Haupt, 2018; Restrepo & Christiaans, 2004) note that the early phases of the design process entail the phases in which information processing is the most intensive as a result of problem structuring and preliminary problem solving cognitive phases (Goel, 1995). The purpose of these cognitive phases is to understand the scope and features of an ill-structured design problem and to develop preliminary design solutions (Goel, 1995; Visser, 2009; Haupt, 2013).

Designers typically engage in problem structuring when they consider the needs of a user, the intentions of a client, the availability of resources, design constraints, requirements and limitations (Goel, 1995). Closely aligned, designers generally engage in preliminary problem solving when they generate possible solutions, write down the design specifications, clarify design ideas, sketch preliminary drawings, and evaluate existing solutions (Goel, 1995).

From a STEM perspective, the ill-structured nature of design problems implies that learners will not, for example, be able to readily find design solutions by merely applying specific mathematical, scientific or technological knowledge in a routine or structured way (Dym et al., 2014). STEM design problems are furthermore regarded to be ill-defined because they typically have several acceptable solutions that could solve the initial design problems (Dym et al., 2014; English et al., 2017; Jonassen, 2011).

The purpose of the integrated STEM activity in this study was to elicit a design process from the participants. The learner participants had to engage in a design process in order to design a solution to the given STEM task. In order to do this, the participants had to explore the design problem, formulate design objectives and possible constraints, generate and develop several design solutions, and compare and select suitable designs (Stempfle & Badke-Schaub, 2002).

1.7 CONCEPTUAL FRAMEWORK OF THE STUDY

Although I view the world of learners' design cognition to be the result of an interplay between internal and external realities, I acknowledge the idea that the way in which learners engage in designing requires multiple paradigms to fully appreciate the complexity thereof. My initial exploration of existing literature on learners' design cognition revealed a variety of internalist and externalist frameworks, yet, in my view, each seems restricted to some subset of the totality of activities of designing. As a result of there being limited frameworks available to guide studies on the manner in which learners solve design problems during integrated STEM tasks (English & King, 2015; Jackson et al., 2015; Wendell et al., 2017), ongoing research is required on the way in which learners' designing can be mediated through social, conceptual and physical structures while engaging with ill-structured problems.

Against this background, I compiled a conceptual framework by drawing on Extended Design Cognition and Activity Systems Theories in order to explore the participants' dynamic interactions with social, conceptual and physical structures that may have affected their design thinking. I thus adapted the Extended Design Cognition Theory of Haupt (2015) by incorporating elements from Engeström's (2015) Activity Systems Theory, as captured in Figure 1.1.

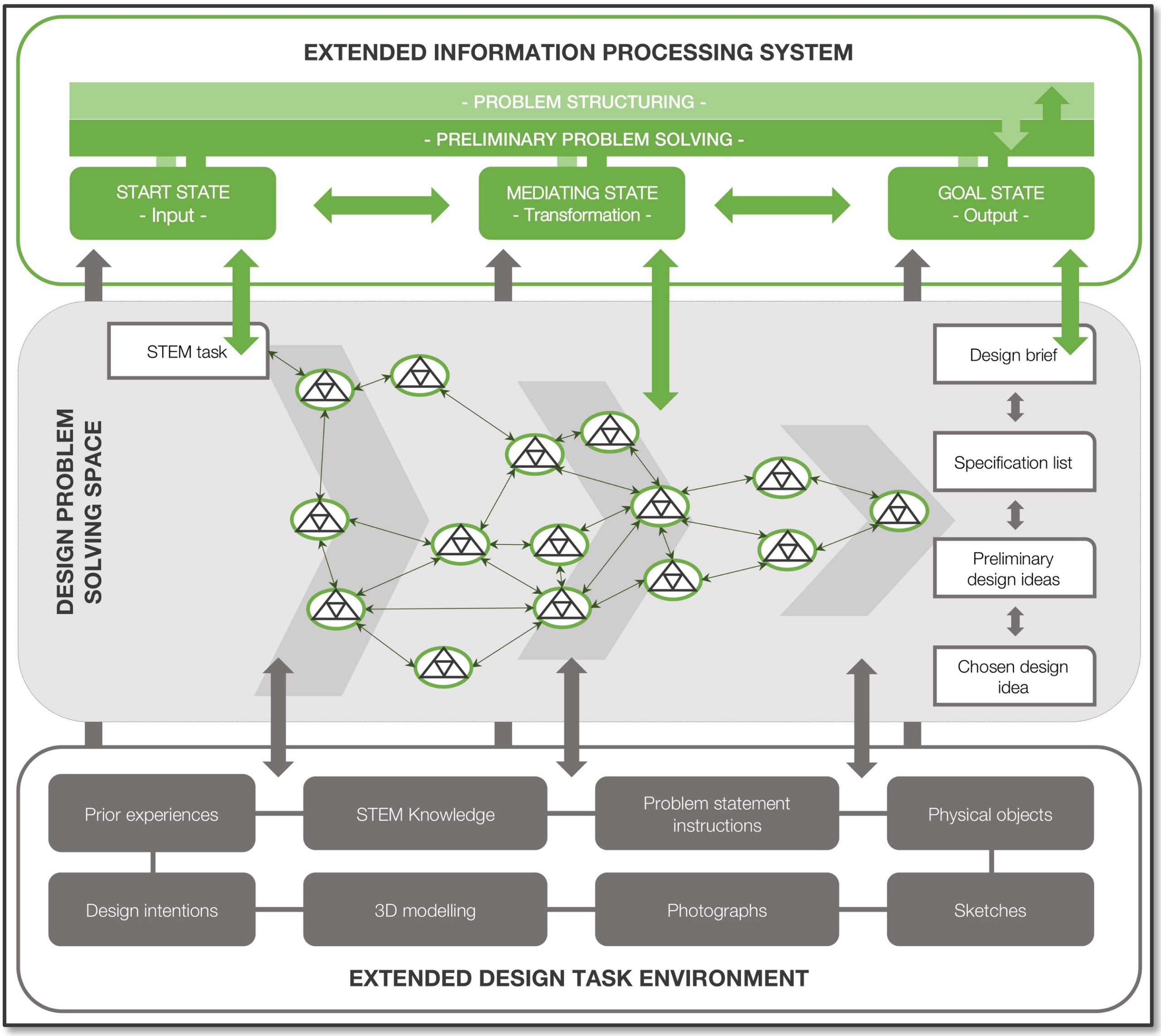


Figure 1.1: Conceptual framework

I thus primarily relied on the Extended Design Cognition Theory of Haupt (2015), which is rooted in the integration of Information Processing Theories of designing (Goel, 1995; Newell & Simon, 1972) and embodiment principles (Anderson, 2003). This theory rests on three theoretical constructs, namely, the extended information processing system, the extended design task environment, and the design problem solving space, which I explain in more detail in Chapter 2. In essence, I viewed a triad of learners engaging in designing as an extended information processing system embedded in an extended design task environment. The result of their interactions in the design task environment gave rise to the design problem solving space. The design problem solving space consisted of various design moves where the groups of participants interacted with social, conceptual and physical sources of information.

I also integrated Activity Systems Theory (Engeström, 2015) in order to understand the underlying structures with which the participants interacted in each design move. These interactions can be seen in the context of the members of a design community, the physical and conceptual tools available to mediate a community's design objects, and the rules and division of labour that may affect the mediating tools in a community's design objects. In summary, I used Haupt's (2015) Extended Design Cognition Theory as an organising structure and its constructs as a-priori criteria for examining learners' design cognition. This was then informed by Engeström's (2015) Activity Systems Theory in identifying participants' interactions with social, conceptual and physical structures. In Chapter 2, I explain the conceptual framework in more detail.

1.8 PARADIGMATIC PERSPECTIVES

In the following subsections, I briefly introduce the epistemological and methodological paradigms that directed this study. These are further contextualised for this study in Chapter 3.

1.8.1 Epistemological paradigm

I took a critical realist stance based on the views of Bhaskar (1998) that critical realism is a paradigm primarily concerned with ontology. As such, critical realism is taken as being grounded in ontological realism, which implies the belief that psychological structures and mechanisms exist independent of researchers' consciousness thereof (Danermark, Ekstrom, Jakobsen, & Karlsson, 2002; O'Mahoney & Vincent, 2014; Sayer, 2010). This means that for critical realists, what is known about reality is separate from what reality actually is. To this end, Danermark et al. (2002, pp. 5-6) explain that “there exists both an external world independently of human consciousness, and at the same time a dimension which includes our socially determined knowledge about reality”. A critical realist stance allowed me to study the observable and unobservable reality of learners’ thinking processes by combining the socially constructed theoretical frameworks of Extended Design Cognition (Haupt, 2015) and Activity Systems Theories (Engeström, 2015) in moving towards a new lens through which to view the ontology of learners’ thinking processes.

A key tenet of critical realism relates to the world being stratified into three different ontological levels, namely an empirical level (what can be empirically observed), actual level (what actually happens, whether it can be observed or not) and real level (the underlying structures and mechanisms for what actually happens). Based on the view that reality can be stratified across three levels, I was able to conceptually decompose the cognitive system of each group of participants into core elements consisting of internal and external information input, action, mechanisms, context and output representations. These discrete elements guided me in defining events during the participants’ processes of designing from which I was able to explore, describe and explain the underlying cognitive mechanisms of their design problem solving processes. To this end, critical realism’s sensitivity to causality enabled me as researcher to investigate the underlying mechanisms as to why problem solving events transpired, as explained by Easton (2009).

In summary, a critical realist stance can enable researchers to implement novel ways when investigating complex cognitive phenomena in a holistic manner (Wynn & Williams, 2012). Furthermore, critical realist research can potentially respond to the calls for theorisation and, for example, create learning theories in technology education that are systems-orientated and may identify the underlying mechanisms that connect chains of thoughts and complex interactions during design activities (Grover, Lyytinen, Srinivasan, & Tan, 2008; Wynn & Williams, 2012). To this end, a critical realist stance implies the possibility of design researchers developing in-depth causal explanations for the way in which learners solve design problems during STEM activities. When utilising critical realism, researchers can focus on the breadth of physical and conceptual tools, social interactions, and environmental factors which can, in turn, play a causal role in the occurrence of participants' design problem solving.

1.8.2 Methodological paradigm

I followed a parallel QUAL + quan mixed methods approach (Creswell, 2014; Teddlie & Tashakkori, 2009, 2012) in my attempt to empirically access the cognitive mechanisms involved in Grade 8 learners' design cognition. While designing, the manner and frequency in which the participants generated design moves in time thus yielded both qualitative and quantitative data. As a result, I generated data by giving all groups of participants an open-ended design task, documenting their actions and dialogue through video-recording and later transcribing the process of design as it happened *in situ*. In addition, the participants concurrently generated written notes, sketches and 3D models, which formed part of the raw data that I analysed.

The qualitative data in this study therefore consisted of spoken utterances, written notes, sketches and 3D models representing the participants' cognitive events. The quantitative data entailed the temporal instances that participants generated, the frequencies and distributions of cognitive events that I converted from qualitative interpretations (Teddlie & Tashakkori, 2009), and the quantitative results of the linkograph analyses. The latter included the directionality of moves and link indexes, which I could also qualitatively interpret.

As part of the data analysis that I completed, I aimed to identify the cognitive phases of the participants' design processes, the problem solving goals they addressed, as well as their interactions with social, conceptual and physical structures during each of the cognitive phases. In identifying their interactions with conceptual and physical structures, I was able to note instances where direct perception seemingly played a role in providing information, and where the participants used STEM knowledge. I was furthermore able to establish instances where written notes, sketches and 3D models supported the participants' design thinking.

For this purpose, I used qualitative data that I could interpret as quantitative instances to be analysed in terms of simple descriptive statistics, and later interpret the converted quantified information back into qualitative interpretations (Morse, 2002). Coding, analysing and interpreting the data both qualitatively and quantitatively allowed me to gain a deeper understanding of the participants' interactions with conceptual, physical and social structures (Johnson & Onwuegbuzie, 2004).

As such, my decision to follow a mixed methods approach was based on three main reasons. Firstly, a mixed methods approach allowed me to generate qualitative and quantitative data, which contributed to a better understanding of the participants' design processes than what one method would allow (Creswell & Plano Clark, 2018; Teddlie & Tashakkori, 2012). Secondly, I could verify quantitative results relating to the participants' design moves, problem solving goals and cognitive phases by referring to the participants' qualitative external representations (Creswell & Plano Clark, 2018; Teddlie & Tashakkori, 2012). Thirdly, since verbal protocols generate a large amount of qualitative data, a mixed methods approach allowed me to interpret and describe the generated external representations by means of frequencies and distributions in order to gain insight into their cognitive nature (Creswell & Plano Clark, 2018; Teddlie & Tashakkori, 2012).

1.9 OVERVIEW OF RESEARCH DESIGN AND METHODOLOGICAL STRATEGIES

The research design I selected directed this study and decisions regarding data generation, documentation and analysis. In the following sub-sections, I briefly introduce these methodological choices. I elaborate on my discussion in Chapter 3.

1.9.1 Research design

I utilised a multiple case study design (Stake, 1995, 2006; Yin, 2018) as this choice enabled me to systematically explore a real-world phenomenon situated in a natural setting. This approach enabled me to generate new knowledge by gaining an in-depth understanding of different groups of participants' design cognition during the early phases of the design process. In this manner I could benefit from the advantages of case study designs that allow researchers to generate thick descriptions and gain in-depth understandings of specific people, activities, policies, strengths, challenges, relationships and events within bounded systems (Creswell & Plano Clark, 2018; Stake, 2006). If a number of cases are integrated into a single study (such as in this study), it is referred to as a multiple case study design (McMillan & Schumacher, 2014). In this regard, Yin (2018) notes that a case study design can be more compelling and the overall study more robust if a researcher includes multiple cases.

In this study, I namely investigated three cases situated in three different medium-resourced schools. I regard a multiple case study design as suitable for this investigation as I aimed to understand how the participants in each case engaged in a STEM task within the context of technology classrooms (Stake, 1995, 2006; Yin, 2018). Furthermore, I attempted to determine how the participants solved their design problems by studying each group of participants as an integrated cognitive system. This implied that I could analyse the actions and dialogue of each group of participants in terms of the social, conceptual and physical structures with which they interacted through the lenses of the Extended Design Cognition and Activity Systems Theories.

When research is based on a small number of cases, it is often viewed as being beneficial when the researcher has little control over events. In the case of this study, designing was taken as a complex real-world activity that cannot be controlled precisely (Cash, Hicks & Culley, 2015; Wynn & Williams, 2012). In addition, case study research is often undertaken when the area of interest is poorly represented in literature, or when the aim is to provide insight rather than obtain general rules (Wynn & Williams, 2012; Yin, 2018). Owing to the small number of cases involved in this study, I realise that the findings and conclusions cannot be generalised or that I cannot make universal claims for school-based STEM practices, however, based on the selected approach and epistemology, the findings may add insight into the field of learners' design cognition and be transferred to similar research contexts.

1.9.2 Selection of cases and participants

In selecting suitable cases, I followed the criteria suggested by Stake (2006). As a result, I was guided by the following questions: *Are the cases relevant to the object of study? Do the cases provide diversity across contexts?* And, *Do the cases provide good opportunities to learn about complexity and contexts?* A detailed description of each of the selected cases and the relevant contexts is provided in Chapter 3.

In selecting the three cases, I relied on both convenience and purposive sampling. I used convenience sampling (Creswell & Plano Clark, 2018; McMillan & Schumacher, 2014) to gain access to three medium-resourced high schools situated in the Tshwane

West and Tshwane South districts in the Gauteng Province of South Africa. I gained access to the schools through the 4th year student teachers whom I was teaching at the time. These students were in their final year of study at the University of Pretoria, and were doing their practicum at the selected schools. In this way, I indirectly gained access to the three research sites *via* gatekeepers (Creswell, 1998), who I knew well and regarded as partial insiders at the schools due to them knowing the schools and their contexts. These student teachers subsequently introduced me to senior technology teachers at the respective schools with whom I discussed my research and through whom I could subsequently meet the school principals and obtain permission to undertake this study.

Even though the three selected cases were conveniently available, my central focus was to collect rich data on the participants' interactions with social, conceptual, and physical structures that engendered learners' design problem solving (Stake, 1995, 2006; Yin, 2018). As such, I had to ensure that the cases met certain selection criteria, which I discuss in more detail in Chapter 3, thereby also applying the principles of purposive sampling (Creswell & Plano Clark, 2018; McMillan & Schumacher, 2014).

In selecting the participants, I requested the three senior technology teachers to each identify six Grade 8 participants (two groups of three learners each) in the respective schools. The teachers were guided by certain selection criteria, such as the participants being top performers in Science, Mathematics and Technology subjects; being able to work well with peers (other participants in the group); and being able to communicate effectively in terms of both verbal and visual representations. After generating data with the six groups of participants (18 learners in total), I once again relied on purposive sampling (Creswell & Plano Clark, 2018; McMillan & Schumacher, 2014) to select three of the initial six groups for in-depth data analysis purposes. My choice of these groups was based on theoretical saturation and information redundancy that the three cases provided, against the background of my conceptual framework (Babbie & Mouton, 2006).

1.9.3 Data generation, documentation and analysis strategies

Based on the critical realist stance I took, as well as the multiple case study research design that I implemented (Stake, 1995, 2006; Yin, 2018), I included multiple data sources (O’Mahoney & Vincent, 2014; Wynn & Williams, 2012). My reason for this relates to the attempted depth of my understanding as well as the rigour of this study. My choice of data generation strategies was furthermore influenced by my own belief that learners’ design cognition can be studied *in-situ* (Ball & Christensen, 2018), which led to my choice of a Think Aloud Verbal Protocol study (TAPS) method to capture the participants’ design cognition. For data documentation, I utilised audio and video-recordings, while relying on linkography to analyse the data. In this section, I introduce the various methodological strategies that I utilised, which I further elaborate on in Chapter 3.

1.9.3.1 Data generation and documentation

Data generation took the form of a *Think Aloud Protocol Study* (TAPS), which included the participants’ verbal utterances, original written notes, sketches and 3D models. As such, I relied on TAPS and observation for data generation purposes. Data were captured by means of audio-visual recordings, as well as the participants’ written notes, sketches and 3D models. In order to document all of the raw data, I relied on photographs and transcriptions of the recordings.

I specifically attempted to create a naturalistic learning environment in order to elicit the participants’ normal and undisturbed thought processes, while I took on the role of observer. I selected triads of participants to ensure verbal fluency in the participants’ dialogues (Fox-Turnbull, 2013; Welch, 1999) and to allow the groups of participants to contribute to a natural technology environment. Even though conventional protocol studies on open-ended design problem solving often involve the thought processes of individual learners, such studies generally neglect the role of the external task environment in learners’ thinking processes (Ericsson & Simon, 1993). I thus adapted this approach to TAPS in an attempt to encourage the naturalistic behaviour of the participants, taking into account the environment in which they solved the STEM task.

I followed the standard approach of TAPS in terms of the guiding four steps for such studies (Ericsson & Simon, 1993). As step one involves the designing of a STEM task that is consistent with the requirements of ill-structured design problems and integrated STEM activities (Capraro et al., 2016; Capraro et al., 2013), I adapted the STEM task for this study from a prescribed textbook (Bosch, Tarling, Hendricks, &

Mackay, 2013) on the basis of the participants' previous work in science, mathematics and technology education, according to the national school curriculum. The second step entailed my preparation of the research setting to enhance effective elicitation of the learners' design cognition. In the various research settings, I set up a space in each classroom for learners to engage with the STEM task and provided them with basic stationary items, tools and materials, which they could interact with during designing.

The third step involved the audio-visual recording of the participants' design problem solving processes. Once the recordings started, I handed each group of participants their STEM task. During the recordings, I took care not to influence the participants' thinking processes. The final step of TAPS that I employed entailed the collection of written notes, sketches and 3D models after the recordings had been completed. In order to document the generated audio-visual data, I transcribed all the verbal utterances for each session, and photographed the visual data sources.

1.9.3.2 Data structuring, analysis and interpretation

Data analysis and interpretation commenced after completion of the recordings and documentation of the TAPS. In applying critical realism principles (Danermark et al., 2002; Edwards, O'Mahoney & Vincent, 2014; Wynn & Williams, 2012) my data analysis and interpretation relied on concepts embedded in the conceptual framework that guided this study. I commenced with data analysis by creating a core quantitative sheet indicating textual transcriptions with temporal measurements of instances and utterances (Goel, 1995; Haupt, 2013). After combining the textual transcriptions with the time stamps, I proceeded with data structuring.

Data structuring involved the process of editing, segmenting and summarising data into macro-, meso- and micro- levels of analysis, as prescribed by Ash (2007). During data structuring, I was able to segment the verbal and visual data into design moves, according to the guidelines provided by Goldschmidt (2014). Once the data were segmented into design moves, I could start the qualitative coding procedures, according to my conceptual framework. I started the coding process by executing a preliminary content analysis based on time, cognitive events, cognitive phases and the mode of output. Next, I coded the verbal data in terms of the various layers, which included my coding of the design intentions, problem solving goals, interactions with internal and external sources, cognitive operators and the physical movements that the participants made during designing. The result of this phase of my analysis process was a list of codes which I could then interpret both qualitatively and quantitatively.

In order to generate linkographs, I coded the links between design moves (Goldschmidt, 2016). All of the links coded in a linkograph are essentially backlinks as such design moves link to posterior moves (Goldschmidt, 1990). Once all the backlinks had been coded for each design session, I could also retroductively identify forward links between earlier moves and moves made later in time. The result of my coding of the backlinks produced numerical data in terms of the number of design moves generated, the type of design moves generated, and link indexes, which provided an indication of the connectivity of thoughts during each design session. Finally, I combined the qualitative coding procedures I completed with the linkograph analysis in order to identify trends and relationships between the way in which the participants interacted with social, conceptual and physical structures, and the number and types of design moves that were generated.

1.10 ETHICAL CONSIDERATIONS

In involving learners between the ages 13 and 15, I was guided by the ethical principles of informed consent, voluntary participation, privacy, trust and safety from harm (Babbie & Mouton, 2006; McMillan & Schumacher, 2014). For this purpose, I obtained permission to conduct my research from the Ethics Committee of the University of Pretoria's Faculty of Education, the Gauteng Department of Education (Appendix A1), the District Directors of the different areas in which each school was situated (Appendix A2), each of the three schools' principals (Appendix A3) and the respective School Governing Bodies (Appendix A4) where the research was conducted before commencing with this study. In addition, I requested permission from the three senior technology teachers (Appendix B1) in whose classes I video-recorded the STEM tasks and obtained informed consent from the parents (Appendix B2) of the learners who participated in the study. I also obtained assent from the learner participants themselves (Appendix B3).

Throughout the study, I respected the principle of voluntary participation. In this regard, I respected the participants' right to withdraw from my study at any time if they wished to do so (Babbie & Mouton, 2006; McMillan & Schumacher, 2014). Prior to commencement of the study, I thus informed the participating learners about the nature of this study as well as their role in it (Babbie & Mouton, 2006; McMillan & Schumacher, 2014). I also emphasised that they were not obliged to participate and could withdraw at any time if they wanted to do so.

Before undertaking data generation, I aimed to establish respectful and trusting relationships with the participants (Babbie & Mouton, 2006; McMillan & Schumacher, 2014). When interacting with the learner participants, I took ample time to discuss and explain what their role in the study entailed or to clarify any questions or concerns that they had. I furthermore maintained a trusting relationship with the participants by encouraging regular discussions with them for the duration of this study (Babbie & Mouton, 2006; McMillan & Schumacher, 2014).

It was of the utmost importance to ensure that none of the participants were harmed during the course of the study. In order to protect the participants from harm, I paid particular attention to what the participants were doing in order to identify any potential signs of harm (Babbie & Mouton, 2006; McMillan & Schumacher, 2014). Should there have been an incident of suspected harm, I had contingency plans in place to immediately withdraw the participants from participation. However, no such incidents occurred. In safeguarding the participants' privacy, I respected the principles of confidentiality and anonymity by removing all identifying features of the participants for dissemination of the results and findings (Babbie & Mouton, 2006; McMillan & Schumacher, 2014). In this regard, I discussed ethical principles with the videographer, who subsequently signed a confidentiality agreement (Appendix B4). In terms of data storage, all raw data generated during the TAPS procedures are stored in a locked cabinet at the University of Pretoria for the required duration of 15 years.

1.11 QUALITY CRITERIA

I adhered to Babbie and Mouton's (2006) guidelines for quality research, as well as the measures for quality case study research as postulated by Yin (2018). As such, I attended to the criteria of credibility, transferability, dependability, confirmability and authenticity (Lincoln & Guba, 1985) to generate trustworthy findings.

Credibility relates to the degree to which I was able to identify the presence or absence of cognitive, physical and social structures and problem solving events, and the relationships among these. *Transferability* implies the applicability of a study's findings to other contexts (Lincoln & Guba, 1985; Babbie & Mouton, 2006). In striving for *confirmability*, I include a trail of evidence in this thesis (Babbie & Mouton, 2006), allowing the reader to determine to what extent my conclusions, interpretations, and recommendations can be traced back to the raw data. Next, the *dependability* of this study is indicated by the extent to which I can demonstrate that my coding and findings are consistent and repeatable (Babbie & Mouton, 2006). Finally, *authenticity* in this study refers to whether or not the results and findings provide a true description of the participants, contexts and events (Lincoln & Guba, 1986).

In ensuring rigour during the linkography analysis, I utilised an *inter-coder reliability* technique, i.e. a reliability technique in which corresponding codes are found by two different coders for the same data set (Salman, Laing, & Connif, 2014). The strategies that I utilised to enhance the quality of this study are discussed in more detail in Chapter 3.

1.12 OUTLINE OF THE THESIS

This thesis consists of six chapters. Chapter 1 provides an overview of the study with specific reference to the relevant background, problem statement and rationale, as well as the purpose of the study. After formulating research questions and defining central concepts, I introduce the conceptual framework that guided me, and state my epistemological and methodological paradigms. I also state the methodological decisions that I made for generating, documenting and analysing the data. I conclude Chapter 1 by discussing the ethical guidelines that I adhered to and briefly refer to the quality assurance measures I followed in ensuring a rigorous study.

In Chapter 2, I discuss the philosophical underpinnings of the nature of technological knowledge, objects and activities in order to provide a foundation for understanding how learners may use STEM knowledge when they design socio-technological objects. Subsequently, I discuss the perspective of designing as problem solving using

Systems Theory as a meta-theoretical framework in which I situate Extended Design Cognition and Activity Systems Theory. I conclude Chapter 2 by explaining my conceptual framework and the way in which I adapted existing theory in conceptualising a novel framework that allowed me to investigate learners' design cognition.

Chapter 3 entails comprehensive explanations of the research process and methodological choices I made in undertaking this study. I discuss, *inter alia*, the critical realist stance I took in conducting a parallel mixed methods study. I position my study within the selected multiple case study research design, and explain how I selected the cases and participants. I provide a detailed account of the data generation, documentation and analysis methods that I employed, after which I discuss the quality criteria to which I strived to adhere. Finally, I explain the ethical considerations I respected when conducting this research.

In Chapters 4 and 5, I present my results and findings based on both the qualitative and quantitative data generated in this study. In Chapter 4, I present the general linkography analysis of each group of participants' design processes, and discuss the social and conceptual interactions of each group of participants during designing. Next, I discuss the participants' interactions with physical structures in Chapter 5, as well as their integrated interactions with conceptual and physical structures simultaneously. To this end, I situate the results that I obtained within existing literature in both Chapters 4 and 5. Throughout, I indicate correlations with existing literature, as well as contradictions and areas where my study adds new knowledge.

In Chapter 6, I address the research questions, thereby coming to conclusions. Next, I contemplate the potential theoretical, methodological and practice-related contributions of this study. Finally, I reflect on the limitations and challenges experienced during this study and make recommendations for training, practice and future research in integrated STEM education.

1.13 CONCLUSION

In this chapter, I presented background and contextual information on the challenges often faced by teachers for curriculum delivery in integrated STEM education, more specifically in the South African context. I explained how limited empirical research on design problem solving, as well as the need for ongoing research on learners' design cognition are core to understanding design thinking. Against the background of these arguments, I stated the purpose of my study and formulated research questions. After introducing and contextualising my research focus and purpose, I introduced the paradigms, research design as well as data generation, documentation and analysis procedures I selected. These choices are discussed in more detail in Chapter 3.

In the next chapter, I focus on existing theoretical frameworks describing the interplay between social, conceptual and physical structures during design problem solving. I highlight the need for integrated frameworks in order to better understand the underlying cognitive mechanisms of learners' design cognition. Against the background of my discussion on what is known in Chapter 2, I describe the empirical investigation that I undertook in Chapter 3.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In the previous chapter I presented background information, as well as the context and rationale of this study. I formulated research questions and provided a brief overview of the selected paradigms that I utilised. I also explained the research process by means of a concise summary of the methodological choices I made.

In this chapter I discuss existing literature in the field of designing in technology education as background to compiling a conceptual framework for this study. To this end, I explore the philosophy of technology, specifically focusing on the general nature of technological objects, technological knowledge, technological activities and technological volition. Next, I focus on the nature of design problem solving and explain design cognition from a Systems Theory perspective as well as an Extended Cognition and Activity System Theory perspective, which form the foundation of my conceptual framework. I conclude the chapter with an explanation of the conceptual framework that guided me in undertaking this study.

2.2 BACKGROUND ON TECHNOLOGY AS A SUBJECT IN SOUTH AFRICAN SCHOOLS

About 2.4 million years ago, primitive human beings engaged in tool making practices in order to create tools for food and shelter. As such, tool-making as a technological activity was a first attempt to solve problems in order to satisfy basic survival and safety needs. Over the years, human beings have developed and refined their capability to design and make artefacts that can solve socio-technological problems. Currently, the focus no longer falls on the technological artefacts that human beings design and make, but also on people's ability to use these, manage, assess and understand them. Therefore, at present, the main aim of technology education is to develop a technologically literate citizenry who will have the ability to design, manufacture, use, manage, assess and understand technological knowledge, processes, artefacts and volition (De Vries, 2016).

Technology was introduced into the South African education system as a compulsory subject for all Grade R to 9 learners in 1998. The first Technology curriculum, Curriculum 2005, was grounded in an outcomes-based education approach and replaced the previously known ‘industrial arts’ subjects (Ankiewicz, de Swardt, & Engelbrecht, 2005). The purpose of the Technology subject was to provide learners with the opportunity to creatively solve real-world socio-technological problems by applying technological knowledge, skills and resources in a purposeful way (Department of Basic Education, 2011). In 2009, the Minister of Basic Education, Ms Angie Motshekga, declared that the ‘death certificate’ for OBE had been signed (Motshekga, 2009). In an attempt to strengthen the curriculum and improve the general quality of teaching and learning conditions in South African schools (Department of Basic Education, 2010), the Curriculum Assessment and Policy Statement (CAPS) was developed and subsequently implemented in 2011.

Based on the new CAPS document, Technology lost its status as a separate subject in the Foundation and Intermediate phases (Grades R-4). Consequently, Technology was integrated into the Grades R to 3 Life Skills subject, and into the Grades 4-6 Natural Sciences subject as part of the CAPS curriculum. Some of the reasons provided for this integration of Technology into other subjects are related to efforts to reduce the number of subjects in the Foundation and Intermediate phases. However, in the Senior phase (Grades 7-9), Technology has remained a separate compulsory subject for all learners.

Currently, in the CAPS document for Technology, ‘Technology’ is defined as “the use of knowledge, skills, values and resources to meet people’s needs and wants by developing practical solutions to problems, taking social and environmental factors into consideration” (Department of Basic Education, 2011, p. 7). This definition of Technology captures two general aims, namely to develop technological literacy among South African learners, and to serve the economic purpose of training future artisans, technicians and engineers, arising from a need in the South African workforce (Department of Basic Education, 2011).

In order to achieve these aims, the Technology curriculum in South Africa specifies three specific aims, namely, that learners need to develop and apply specific design skills to be able to solve technological problems; they need to understand the concepts and knowledge used in Technology and use them responsibly and purposefully; and they need to appreciate the interaction between people's values and attitudes, technology, society and the environment (Department of Basic Education, 2011). In an attempt to address these specific aims, the Department of Basic Education suggests that teaching and learning in Technology should be guided by the design process as a backbone to the subject's methodology (Department of Basic Education, 2011). Core content areas that are regarded as important to be taught to learners include structures, the processing of materials, mechanical systems and control, and electrical systems and control. In the next section, I explore the meaning of technology from a philosophical viewpoint as applicable to this study.

2.3 UNDERSTANDING THE CONCEPT TECHNOLOGY

Even though scholars in the field of technology have attempted to conceptualise technology since the second half of the 19th century, no consensus has been reached among philosophers, historians or scientists about the exact nature of this science (Hoyningen-Huene, 2008). In this regard, Marx Wartofsky (1979, p. 176), commented four decades ago already that:

> *"Technology is unfortunately too vague a term to define; or else, so broad in its scope that what it does define includes too much. For example, technology can be viewed as including all artefacts, that is, all things made by human beings. Since we 'make' language, literature, art, social organizations, beliefs, laws and theories as well as tools and machines, and their products, such an approach covers too much".*

The etymology of the concept 'technology' can be traced back to the Greek word *techne,* which refers to a particular craft knowledge and has been used in the contexts of farming, medicine and art (Nye, 2006; Parry, 2008). The related term 'engineering' is grounded in the Latin word *ingenera*, which refers to human activities of generating and producing (Meijers, 2009).

One of the first attempts to define technology was by Jacob Bigelow (1829), an early philosopher of technology, who mainly conceived technology as a unique body of knowledge. According to Bigelow (1829, p. v), technology can be regarded as "principles, processes, and nomenclature of the more conspicuous arts, particularly those which involve applications of science, and which may be considered useful, by promoting the benefit of society, together with the emolument of those who pursue them". This definition implies that technology is comprised of several interconnected aspects, including physical (product and process), metaphysical (principles), socio-cultural (nomenclature), functional (application of science), beneficial (considered useful), purposeful (promoting societal gains), and economic (emolument) aspects. This range of interconnecting aspects contributes to the challenge of understanding and concisely defining the nature of technology. Bigelow's (1829) definition of technology is furthermore somewhat limiting as it describes technology as a body of knowledge, and not in terms of technological objects, processes and human values.

Many follow-up definitions similarly depict technology as a unique body of knowledge, but do not agree on the nature of knowledge that it entails. Friedrich Rapp, for example, describes technology as a human enterprise, stating that "in simplest terms, technology is the reshaping of the physical world for human purposes" (p. xxiii). As another example, Black (1998, p. 24) defines technology as the "creative, purposeful activity aimed at meeting needs and opportunities through the development of products, systems or the environment". Black (1998) furthermore explains that knowledge, skills and resources are typically used when designing artefacts that can assist people to solve practical problems.

Despite various attempts to succinctly define technology, movements towards defining technology as a fixed collection of phenomena have been discarded due to the concept implying diverse domains. In an effort to provide a structured description, Mitcham (1994) presented a framework more than two decades ago containing four different ways in which technology can manifest. The framework namely refers to technology as objects (ontology), knowledge (epistemology), activities (methodology), and technology as volition (axiology). Contemporary scholars in the field of technology are still guided by this framework in understanding the concept of technology.

2.3.1 Technology as objects

Technology can firstly be viewed as a collection of designed artefacts or systems (Ankiewicz, De Swardt, & De Vries, 2006; Custer, 1995; De Vries, 2016). When taking a philosophical stance regarding technological artefacts, consideration is given to their ontology or 'being'. In ontological discussions about the nature of artefacts, scholars are often concerned about how technical artefacts can be categorised according to their nature (Houkes & Vermaas, 2013), and how technical artefacts can be distinguished from non-technical artefacts (De Vries, 2016). One way of distinguishing between technical artefacts and non-technical artefacts is by focusing on the dual nature of artefacts.

Technical artefacts refer to designed physical objects that are intentionally produced and used in an attempt to realise certain objectives (Kroes, 2009). This description implies that technical artefacts have a dual nature: they have a *physical* nature, which embody designers' and users' intentional functions, thereby also implying a *functional nature* (Kroes, 2009). As objects with a physical nature, technical artefacts fit into the physical or material conception of the world. This means that the physical nature of objects can be described in terms of structural properties such as shape, size, weight, colour, texture, smell, sound and material properties, which include chemical, optical, thermal, electrical, mechanical and magnetic properties (De Vries, 2016; Frederik, Sonneveld, & De Vries, 2011; Kroes, 2009).

As stated, technical artefacts are furthermore designed with a certain function in mind, with users benefitting from artefacts that can fulfil the desired functions (Crilly, 2010). This implies that a technical artefact is designed to do something, thereby implying human intentionality, with users performing actions with technical artefacts for their intended purposes (Houkes, Kroes, Meijers, & Vermaas, 2011). The functional nature of technical artefacts is typically normative, as they require a designer or user who ascribe possible functions to the physical nature of the artefact, which might be appropriate or inappropriate.

In order to be able to choose the best material in a design challenge, learners are required to focus on the relationship between the physical and functional nature of the artefact they are designing. This means that when learners design technical artefacts, they are required to find the most appropriate physical structure that can allow for the realisation of the intended function. In order to find a suitable physical structure, learners in turn require knowledge that links the physical properties of materials with the functional properties of artefacts. If functions are primarily seen as being realised in the physical properties of artefacts, the question however remains as to how these functions may be related to the mental states of learners during designing, which will essentially form part of their design intentions (Houkes et al., 2011; Kroes, 2009). If functions are seen as patterns of mental states, the question furthermore remains as to how learners will embody function in the physical structure of the artefacts they design and make. However, embodying intentionality and function in the physical structure of artefacts can also occur during learners' design tasks.

By studying the mechanisms underlying learners' design problem solving events, I aimed to understand how the structure and function of learners' artefacts are synthesised during designing and making in the early phases of the design process. I was specifically interested in the content of learners' thoughts in terms of the knowledge and information that they used to reason during their design processes, and how this information was embodied in the participants' external representations and final design ideas.

2.3.2 Technology as knowledge

Technological knowledge is sometimes seen as the product of a joint activity between a community of professionals (De Vries, 2016; Meijers & De Vries, 2009). Such a community may consist of a variety of practitioners in the field of technology, such as engineers, architects, technicians, designers and craftsmen that may contribute to the existing body of knowledge in technology. In each occupation, technical norms and standards form part of the communities' technological knowledge (Meijers & De Vries, 2009). In contrast to scientific knowledge, justification criteria are social as it is entirely up to the community of professionals to determine the 'effectiveness' of the knowledge. As such, knowledge on technology may be the result of collective decision making, and can therefore, as a result, be regarded as social constructs.

Technology aims to produce knowledge that is relevant when solving problems for specific contexts and systems (Kroes, 2009; Radder, 2009; Ropohl, 1997). In some cases, technological knowledge can be generalised and applied to other contexts or other design problems. However, such generalisations cannot differ dramatically from the specific contexts in which the knowledge was generated in order to remain practically relevant. Some technological knowledge also includes a normative component (De Vries, 2016; Meijers & De Vries, 2009) due to being related to value judgements.

Several authors indicate that technological knowledge cannot always be expressed in terms of propositions (Compton & Compton, 2013; De Vries, 2016; Meijers & De Vries, 2009). In this regard, Ryle (1984) refers to the term 'knowing-how' to indicate procedural knowledge that cannot fully be expressed in propositions, for example, knowing how to hit a nail with a hammer so that the nail goes straight into a piece of wood. In support, Ferguson (1992) argues that the sketches and drawings that designers produce contain a richness of knowledge that cannot be expressed in propositional terms. As such, an irreducible visual aspect to technological knowledge probably exists, which goes beyond the limits of being stated in propositions. Next, Baird (2004) proposes a material epistemology, arguing that artefacts contain knowledge themselves. This implies that technological knowledge can be embodied in theories and in things, having the potential to generate knowledge and also to express technological knowledge. According to Baird (2004), artefacts can be 'read' in order to view the insights of the designer who designed the artefact. As such, designers' knowledge is seen to be built into technological artefacts, which can be separated from the user's agency and beliefs. This implies that the type of knowledge is seen as 'thing knowledge' – being materials-based, not belief-based.

Various studies distinguish between different categories of technological knowledge that are used by designers during the design process (De Vries, 2005; Stevenson, 2004; Vincenti, 1990). In the current study, I aimed to understand the internal information sources that learners used during the completion of their STEM tasks under the auspices of conceptual knowledge, procedural knowledge and visualisation.

2.3.2.1 Conceptual knowledge

Conceptual knowledge refers to propositional knowledge that can be generalised (principles, laws, heuristics) and is concerned with relationships among facts. This implies that when students are able to identify links between facts, they are said to possess conceptual understanding. With regard to the topic of heat transfer, for example, on which the participants' STEM task was based, learners could potentially see the relationships between convection, conduction, and radiation in order to bring about heat transfer. To this end, McCormick (2006) emphasises that conceptual knowledge is not mere factual knowledge, but consists of situated ideas that give some power to thinking about particular activities.

Although technology has its own body of conceptual knowledge that is unique (De Vries, 2016) technology also draws on knowledge from other subject areas (Daugherty & Carter, 2018; McCormick, 2006). More specifically, philosophical and empirical studies undertaken in professional and school-based design contexts have shown that knowledge used when designing is multi-disciplinary (De Vries, 2016; Kimbell & Stables, 2008). Layton (1994) notes that other knowledge areas, such as science and mathematics can, however, not be merely applied as is, but have to be conceptually deconstructed and reconstructed to be useful for practical purposes. In other words, scientific, technological and mathematical knowledge acquired propositionally must be contextualised if learners are to make connections from these to their own design activities (Pedgley & Sener, 2018).

For the purpose of this study, I considered how the participants used the conceptual knowledge they had previously gained from science, technology and mathematics when doing their STEM task (refer to Chapter 3 for a summary of the conceptual knowledge). I also considered the participants' socio-technological knowledge (Ropohl, 1997), situational knowledge (Venselaar, Hoop, & Drunen, 1987) and funds of knowledge (Moll, Amanti, Neff, & González, 1992). This implies that, in the current study, conceptual knowledge not only referred to scientific, technical and mathematical aspects of artefacts, as is often the case in technological studies, but also to the socio-cultural knowledge of the participants, which provided the conceptual knowledge that guided their intentions for artefacts.

Kimbell and Stables (2008) indicate that when learners are engaged in design learning, in-depth conceptual knowledge of all design components in the early phases is not required. In order to map the level of knowledge that is applied to a design task, these authors use the metaphors of black box, street level and working knowledge (Kimbell & Stables, 2008). Black box knowledge would, for example, indicate that learners do not necessarily know how a concept (heat transfer) works, but they would know that it does, whereas street level knowledge would imply common knowledge (e.g. knowing that certain materials insulate and conduct heat). Lastly, working knowledge would imply that learners know enough to manipulate/modify the product (e.g. knowing that one can use different materials and manufacturing methods to produce food packaging with different functions, behaviours and structures). In this study, I took the view that the level of knowledge being evidenced had to be appropriate to the early phases of the design process – where learners would understand a problem and be able to start finding preliminary solutions.

2.3.2.2 Procedural knowledge

Alexander, Schallert and Hare (1991) describe procedural knowledge as the knowledge of processes, methods of inquiry, skills and routines. Procedural knowledge ranges from simple procedures (e.g. measuring a piece of material with a ruler) to complex procedures (e.g. designing a device). Ropohl (1997) notes that procedural knowledge is generally gained through practice and implies tacit, personal or implicit knowledge. However, unlike conceptual knowledge, procedural knowledge cannot be taught through verbal transmission. Even though procedural knowledge also includes the ability to communicate and manage the division of labour between members of a group, I only focused on procedural knowledge relating to the participants' design thinking processes, and not on their technical manufacturing skills.

Stevenson (2004) distinguishes between three types of procedural knowledge. First-order procedural knowledge includes physical skills that are directed towards known goals and are automatic, fluid, or algorithmic, for example, estimating the size of material or hammering in a nail. Second-order procedural knowledge entails the use of mental skills to achieve unfamiliar goals, such as problem solving, designing or optimising skills. Third-order procedural knowledge includes the skill of switching cognition between the first and second order levels of procedural knowledge, and therefore has a controlling function. In this study, I regarded skills and procedural knowledge as synonymous since first-order procedural knowledge accounted for the physical skills that the participants used, and second-order procedural knowledge for the mental skills on which they relied.

McCormick (1997) highlights an interrelationship between conceptual and procedural knowledge, stating that "it is the possession of conceptual knowledge that makes possible the effective use of procedural knowledge of problem solving" (McCormick, 1997, p. 149). Within procedural knowledge, McCormick (1997) describes another type of knowledge relevant to technology, which is referred to as strategic knowledge. Learners generally rely on strategic knowledge to progress during designing when their existing knowledge base is not sufficient to solve problems. McCormick (1997) labels strategic knowledge as the know-what-to-do, how-to-do-it and when-to-do-it knowledge. Furthermore, strategic knowledge includes metacognitive knowledge, which McCormick (1997) labels as the knowing-how-well-you-are-doing-at-any-point-in-time knowledge. However, as mentioned in the previous section, no level of procedural knowledge will be of benefit if learners do not possess conceptual knowledge (McCormick, 2006).

2.3.2.3 Visualisation

Visualisation relates to the ability to think and externally represent knowledge embodied in different modes of media. As such, visualisation entails the intertwinement of conceptual and perceptual processes playing an important role as a driving force for solving design problems (Härkki, Seitamaa-Hakkarainen, & Hakkarainen, 2018; Lane, 2018; Worsley & Blikstein, 2016).

In existing literature, visualisation is viewed from two different perspectives. First, from the classic internalist view, designers are seen to create external visualisations by giving shape to drawings, 3D models and words based on pre-existing ideas stored in their minds (Ingold, 2010; Roth, Socha, & Tenenberg, 2017). In Figure 2.1, this process is illustrated on the right side of the diagram.

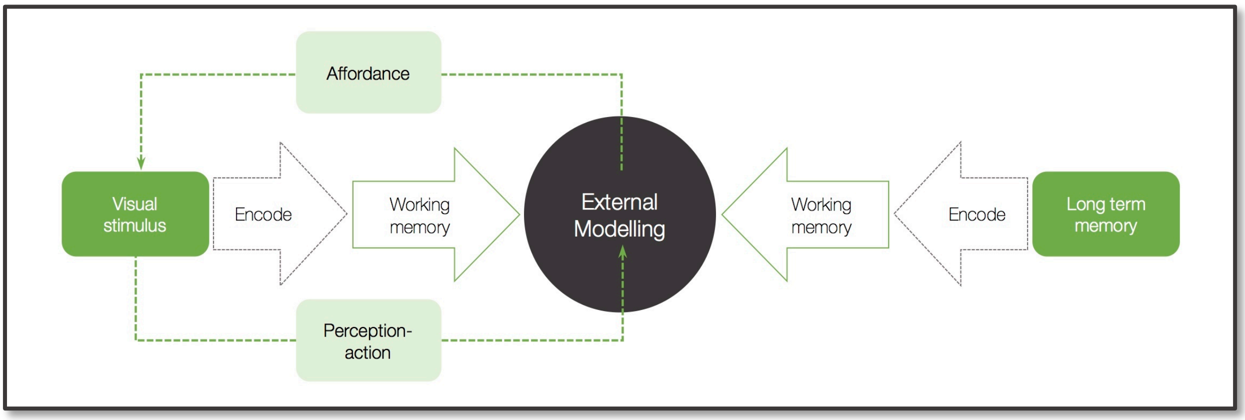


Figure 2.1: Mapping visual processing theory with external modelling (adapted from Lane, 2018)

When learners, for example, thus purposefully engage in mark making or prototype making, the interaction between pen and paper or hand and materials is primarily driven by the memory system to generate visual mental images which may be projected on materials. However, from an extended cognition view, designing is viewed as a decentralised activity in the sense that visualisation is seen to emerge from the interactions of one or more designers with their physical environments, which none of the individual contributing designers had in mind previously (Roth et al., 2017). From this perspective, visualisation can be seen as the result of the moment-to-moment interplay between designers' prior knowledge encoded in working memory, the direct perception of affordances in the environment, and acting upon perceived affordances (shown on the left side of Figure 2.1).

In this study, I did not attempt to discuss the complexity of visualisation, yet focused on the dynamic role that sketching, writing and 3D modelling played during the participants' completion of the STEM tasks. Therefore, I regard visualisation as the act of sketching, 3D modelling and gesturing. I furthermore consider the physical sketches and 3D models of activities as objects which in turn can be perceived and interacted with by the participants. By linking cognitive mechanisms to sketches and 3D models as objects, I was able to make theoretical associations with the Extended Design Cognition and Activity Systems Theories, relevant to my conceptual framework (refer to Section 2.6).

2.3.3 Technology as activities

Mitcham (1994) identifies various technological activities, such as crafting, inventing, designing, manufacturing, working, operating and maintaining. I mainly focused on designing in this study. As such, designing cannot be considered as exclusive to the domain of trained professional designers, but can also occur in classroom settings. Taken in its broadest sense, designing is regarded as a basic human capacity that is put to use when engaged in intentional activity – that is, when intending to have some effect (Kimbell & Stables, 2008; Nelson & Stolterman, 2012). Designing is characterised by the use of forethought, imagining the future, and reducing the need for trial and error decision making (Kimbell & Stables, 2008; Nelson & Stolterman, 2012).

Immersing learners in design processes can facilitate their engagement with scientific, technological and mathematical knowledge (Strimel & Grubbs, 2016). As a result, STEM education initiatives emphasise the importance of design processes (Kelley &

Knowles, 2016; Wells et al., 2016). However, using the design process to acquire STEM content has also been critiqued in the past and present, referring to challenges regarding the lack of clear and consistent definitions of designing (Kelley & Knowles, 2016; Strimel & Grubbs, 2017), the lack of clear learning progressions of design skills (Marra, Steege, Tsai, & Tang, 2016) and the lack of specified methods and techniques to effectively teach design skills (Kelley & Knowles, 2016).

In an attempt to understand how different groups of learners engage in designing, scholars in Cognitive Psychology suggest that researchers study small increments of thought (Chinn & Sherin, 2014; Goldschmidt, 2014). Design process models state that the design process comprises separate steps or phases and that designers progress from one phase to another, with iterative cycles where necessary. In this regard, such models become obsolete for understanding the nature of learners' thinking processes. Although these design process models highlight the procedural nature of designing, and help teachers to manage learners' design processes, they do not reveal the ontological nature of design thinking (Haupt, 2018a; Sung & Kelley, 2018). This points to the importance of ongoing research in the field, looking at smaller segments of the design process in order to be able to understand how learners think during designing (diSessa, Sherin, & Levin, 2016; Goldschmidt, 2014; Hall & Stevens, 2016).

Internationally, STEM and technology curricula often include design process models comprising steps or phases that learners can follow when attempting to solve design problems. However, research has indicated that design process models may potentially distract students from learning STEM concepts and in this way reduce their abilities to transfer knowledge to other settings or problem scenarios (Goldstone & Sakamoto, 2003; Kaminski, Sloutsky, & Heckler, 2009).

Even though the findings on professional designers' cognitive processes during designing may not necessarily describe school learners' cognition, ongoing research is thus required in this area. Design cognition research that attempts to understand learners' application of design processes can potentially contribute to teachers' improved comprehension of advanced design practices and effective pedagogies for cultivating learners' design skills. Specific research on how individuals and groups of learners design may assist teachers to gain insight in terms of what they can do to help learners improve their design capability (Crismond & Adams, 2012). Without understanding students' cognitive processes during designing, teachers may fail to provide effective instruction and can potentially, for example, reinforce inefficient design behaviours, misconceptions and cognitive habits (Crismond & Adams, 2012; Hynes, 2012).

An increased understanding of learners' cognition during engineering design tasks is also regarded as helpful when wanting to identify and address shortcomings in how learners typically engage in STEM activities (Strimel, 2014). Therefore, despite research indicating the positive impact of design methodology on students' STEM practices, limited research is available related to the improvement of students' higher-order thinking skills during designing (National Academy of Engineering, 2014). In this regard, Tank et al. (2018) indicate that research focusing on learners' use of design to effectively acquire disciplinary STEM content is still emerging.

2.3.4 Technology as volition

The final way in which technology can manifest is technology as volition, which refers to the volition of the designer (Mitcham, 1994). Technologies are associated with a variety of volitional activities, including drives, motivation, aspiration, intentions and choice. In this regard, the phrase 'the will to ...' is found in various definitions of technology (Mitcham, 1994). Although technology as volition may point toward an understanding of the ethical implications of technology or the impact of technologies on the social and physical environment, this did not form part of the focus of this study. Instead, I only paid attention to the learners' design intentions as an organising structure for their emerging thoughts.

Pedgley and Sener (2018) note that during designing, intentions give a purpose, justification, and context for design choices and knowledge use. In the fields of design, the most significant attempts to discuss and empirically study intentions in relation to design activity have been made by Archer and Roberts (1979), Hicks, (1982), Roberts (1993), Norman, Pedgley, and Coles (2004), Trimingham (2008) as well as Mettas and Norman (2011). From these studies, five categories of values which encompass a range of design intentions have emerged, including technical, economic, aesthetic, moral/ethical, and hedonic values. These values provided me with a way in which I could identify learners' design intentions.

According to Ecological Psychology, intentions play a valuable role during problem solving as it harnesses learners' perceptual systems to detect functional information in the physical or social environment which can be acted upon (Young, 2004). The term 'affordance' is used to describe information that provides learners with opportunities for action (Young, 2004). This means that learners will be able to detect affordances in their physical and social environments as they perceive and pay attention to information structures in the environment. This furthermore illustrates how learners' interactions in the social and physical environments will drive their perceptions, which in turn will drive their interactions.

From a pedagogical point of view, learners can be attuned to their physical and social environment to detect relevant information that may assist them in solving design problems. This might, for example, occur when a teacher provides scaffolding by means of environmental stimuli to facilitate learners' design processes, or during collaborative designing when the action of one student can cause another to detect an affordance, enabling the perceiver to address the design intention.

In this study, technology as volition highlights the way in which learners may detect or perceive information based on the constraints imposed by their design intentions, while acting to transform the environment so that new affordances may emerge which can be perceived and acted upon. This implies that teachers need to induce learners to have design intentions that relate to the solving of their design problems, which could guide subsequent perception-action cycles (Young, 2004).

2.4 TRADITIONAL VIEW OF DESIGNING AS PROBLEM SOLVING

The 20th century was marked by a growing interest in 'scientising' the process of designing. During the 1960s, researchers aimed to understand aspects of designing by studying related influences, processes and methodologies (Cross, 2011). One of the main reasons for building theory in design science relates to the argument that in order to design new products, designers need insight in terms of an objective and repeatable design process. This argument however implies the abandonment of intuitive design processes (Cross, 2011) and the importance of a philosophical approach to generic design processes, which has gained field over recent years, once again emphasising the need for ongoing studies in this emerging field of research.

Researchers' attempts to develop generic approaches to design problem solving have resulted in them considering the psychological underpinnings of designing, as evident in the work of, for example, Suwa, Purcell and Gero (1998), Goldschmidt (1991) and Cross (1990). Such studies resulted in designing being viewed as a type of problem solving activity (Dorst & Dijkhuis, 1995; Goel, 1995; Ullman, Dietterich, & Stauffer, 1988) with a strong focus on the unique nature of design problems (Goel & Pirolli, 1992). The focus on design problems culminated in the view that design problems will determine the way in which designers 'know' and 'think' (Cross, 2007; Lawson, 2006). Following earlier studies on the ontological and epistemological nature of designing in relation to generic psychological underpinnings involved in design processes, a philosophy of design was subsequently cultivated that is still emerging. With this study, I strived to make a contribution to this field of interest.

A pioneer in studying problem solving from a psychological viewpoint is Herbert Simon (1969). Based on his work, together with that of Allen Newell, design problem solving can be understood from an information processing approach (Newell & Simon, 1972). In his initial work, *Sciences of the Artificial*, Simon (1969) proposed a close relationship between the nature of ill-structured design problems and the complexity of design processes. The distinction between well-structured and ill-structured problems (Cross, 2011; Goel, 2014; Reed, 2016) was important in my study as I view ill-structured design problems as unique kinds of problems that are characterised by the relationship between the availability of information, the nature of mental representations of problems and the complexity of design processes. I furthermore regard generic characteristics as being present in design problem solving (Goel, 1995; Haupt, 2015; Visser, 2009), irrespective of the design domain or type of design output resulting from the design process.

During the 1970s, design theorists started arguing that available information processing theories on designing were too restricted to study authentic design behaviour due to such theories viewing thinking as solely governed by the brain and subsequent internal processing of information. This narrow view was seen as neglecting the role of external information sources during designing such as the use of sketches, photographs, written notes, diagrams, 3D modelling, and site visits. As a result, the need for an alternative approach to study designing was continuously emphasised in studies undertaken at the time (Dorst & Dijkhuis, 1995; Schön, 1983; Visser, 2004).

In response to the emphasis on designers interacting with their external environments during designing, design researchers subsequently started focusing on theoretical frameworks from an Ecological Psychology perspective (Bucciarelli, 1988; Schön, 1983). Scholars taking the lead in situated design research during this era include Schön (1983), as well as Bucciarelli (1988), with the latter focusing on designing as a social process. However, situated design approaches seemed limited at the time due to theoretical paradigms being rather allusive; the definitions of central notions lacking precision; data generation, analysis and modelling methods not offering tools to derive higher-level descriptions of data; and conclusions often being anecdotal. As such, situated studies in design often presented raw data, rather than providing generalisable and replicable conclusions (Visser, 2004).

Despite the limitations of situated design approaches, I considered these contributions when conducting my research. According to the situated view of the concept, designing can primarily be understood as interactions between designers, physical systems and other people (Greeno & Moore, 1993). Based on this premise, I aimed to examine how learners engaged in a STEM task while interacting with not only conceptual information, but also with their social and physical environments.

In summary, studies embedded in information processing theory typically focus on designers' use of conceptual information in terms of knowledge and representations during design problem solving, yet may neglect the way in which designers interact with and within their social and physical environments. Alternatively, studies in the field of situated designing pay specific attention to the consequences of designers' interactions during designing as well as the influences of the physical and social environment on the design process, yet generally neglect the computational nature of designing and the underlying psychological and conceptual structures. In considering the differences between information processing and situated approaches I came to the conclusion that these two approaches emphasise different design activities albeit to the silencing of others.

To this end, Haupt (2015) recently challenged the traditional boundaries between information processing and situated approaches to designing in a study on the cognitive dynamics of expert designers. Haupt (2015) found that when expert designers are confronted with a design task, they will depend on both internal and external information to solve the problem. Furthermore, Haupt (2015) indicates that expert designers will use their socio-technological knowledge, interactions with the physical environment and their own representational activities to establish a synergistic relationship between internal and external information sources. Of importance for the current study is Haupt's (2015) Extended Design Cognition Theory, which I also considered in order to investigate the way in which learners engage in designing. This implied that I had to consider internal processes taking place in a mental problem solving space where a particular task environment (that extends over internal and external situational environments) served the problem solving process.

Based on the dynamic, changing view of scholars on designing, I focused on an integration of information processing and ecological theories of cognition in explaining learners' engagement in STEM tasks. I furthermore attempted to expand on existing theories that do not focus on the interrelationships between internal conceptual structures, structures in the social and physical environments, and the resulting emerging design events. As such, my study can potentially contribute to existing theory in the field of learners' design cognition by highlighting how learners' interactions with social, conceptual and physical structures can contribute to the development of their thinking processes during designing. In order to investigate this, I selected Systems Theory as an overarching theory.

2.5 UNDERSTANDING DESIGNING FROM A SYSTEMS THEORY PERSPECTIVE

I view the notion of a 'system' and the development of design theories around it as central when aiming to understand learners' problem solving activities during STEM tasks. I thus first discuss the development of Systems Theory in this section, in which my study is situated, and then focus on a functionalist view of systems. More specifically, I explain how I situated my study in General Systems Theory (Von Bertalanffy, 1968) in regarding each situated group of participants as a cognitive system.

2.5.1 Development of Systems Theory

Simply defined, a system refers to a set of structures or parts that interact by means of a set of relationships (Backlund, 2000; Kitto, 2014). A system can be isolated from an environment, and is characterised as either closed or open, depending on whether or not it interacts with an environment (Backlund, 2000; Kitto, 2014). Researchers often utilise Systems Theory to examine groups of structures that function together to produce a specific result. In applying this definition to the current study, I viewed the participants' design events as the result of their interactions with the social, conceptual and physical structures of an information processing activity system. I specifically focused on the relationships between these structures and their dynamics which resulted in the design problem solving events of the participants.

The existing body of knowledge on how systems can be viewed initially followed a reductionist approach (18th century) yet later moved to one of holism. According to the reductionist paradigm, a system is made up of paramount structures resulting in a focus on identifying and understanding the structures within a system when aiming to understand a complete system (Jackson, 2003). Systems can, however, take on forms that are not recognisable from their structures (Jackson, 2003).

To the contrary, Greek philosophers, including Aristotle and Plato, argued that a whole system will emerge from the interactions and relationships between its structures, with the whole system subsequently giving meaning to the structures and their relationships and interactions. For studies in design problem solving, researchers are thus required to not only focus on internal or external structures in the learning environment when explaining the way in which learners engage in designing, but to also study the way in which learners make connections between internal and external resources and how these connections may ultimately result in learners' design problem solving events. This argument led to my decision not to simply focus on reductionist approaches to understanding designing in this study.

Holism, as alternative paradigm, implies that systems are viewed as more than the sum of their structures. Accordingly, the structures that make up a system, the networks of relationships between these and the interactions between structures are all emphasised. This emphasis contributes to an understanding of how structures in a system can interact to bring about and sustain the existence of a whole system. In applying this belief to my research, I assumed that design problem solving events would emerge as a result of the manner in which learners interacted with other people during collaborative designing, the way in which they interacted with information from their memory, as well as how they perceived and interacted with the physical resources in their environments.

Reductionism as the traditional paradigm for studying systems was rejected by the end of the 18th century with the rise of European philosophy, and philosophers such as Kant and Hegel influencing the transition period. Whereas Kant argued that it is useful for humans to think in terms of wholes emerging from the self-organisation of their structures (Jackson, 2003), Hegel (1977) introduced processes into Systems Theory with his theory of dialectical materialism. According to dialectical materialism, an understanding of the whole can follow the systemic unfolding and dynamic interplay between a thesis, antithesis and synthesis. For my theoretical position on design problem solving, I relied on Kant's (1990) notion of self-organisation to understand the decentralised nature of the participants' design cognition. During my data analysis, I relied on Hegel's Dialectical Materialism Theory (Hegel, 1977) to guide my interpretation of the dynamic interactions between the participants and the social, conceptual and physical structures that resulted in their design problem solving events.

2.5.2 Emergence of a Functionalist Systems Theory

Functionalism derived its name from the notion that researchers and practitioners will generally value the importance of ensuring that systems function well in order to promote efficiency, adaptation and survival (Jackson, 2003). From a functionalist perspective, design researchers interested in problem solving may gain an understanding of how designers think during problem solving. They can gain such understanding by using scientific methods to probe for the structures of systems, the interrelationships between these, and the relationships between designers and their environments as systems. The practical application value of functional perspectives in STEM environments lies in teachers being able to optimise learners' problem solving processes and minimise inefficiency during problem solving by planning and organising effective problem solving learning environments (Brown, Danish, Levin & diSessa, 2016; Kirschner & van Merriënboer, 2008; Miyake & Kirschner, 2015).

Ludwig von Bertalanffy was one of the first theorists to propose a functionalist model of systems. Aligned with Kant's (1990) notion of self-organisation, Von Bertalanffy (1950) argues that organisms can be studied as complex wholes, steering away from a focus on the isolated structures of the total system only. In order to develop a systemic view of real-world problem solving, researchers can focus on identifying structures in the learning environment that may contribute to the way in which learners understand and solve problems, describing the connections that learners make between these structures during problem solving, and mapping the dynamics and connections between structures that may result in emergent design problem solving events. To this end, Von Bertalanffy's (1950) developed the General Systems Theory, which provides a framework for researchers to complete these actions.

Von Bertalanffy's (1950) theory can be regarded as a transdisciplinary meta-theory that describes the generic nature of open systems in multiple environments, implying a set of generic principles that can apply to all types of systems. In situating my study within the General Systems Theory, I focused on the inputs, outputs, structures, processes, arrangements, relationships and organisations of social, conceptual, and physical structures that could have influenced learners' design problem solving events. Figure 2.2 provides an overview of General Systems Theory, indicating how a cognitive system is dependent on both internal and external environments.

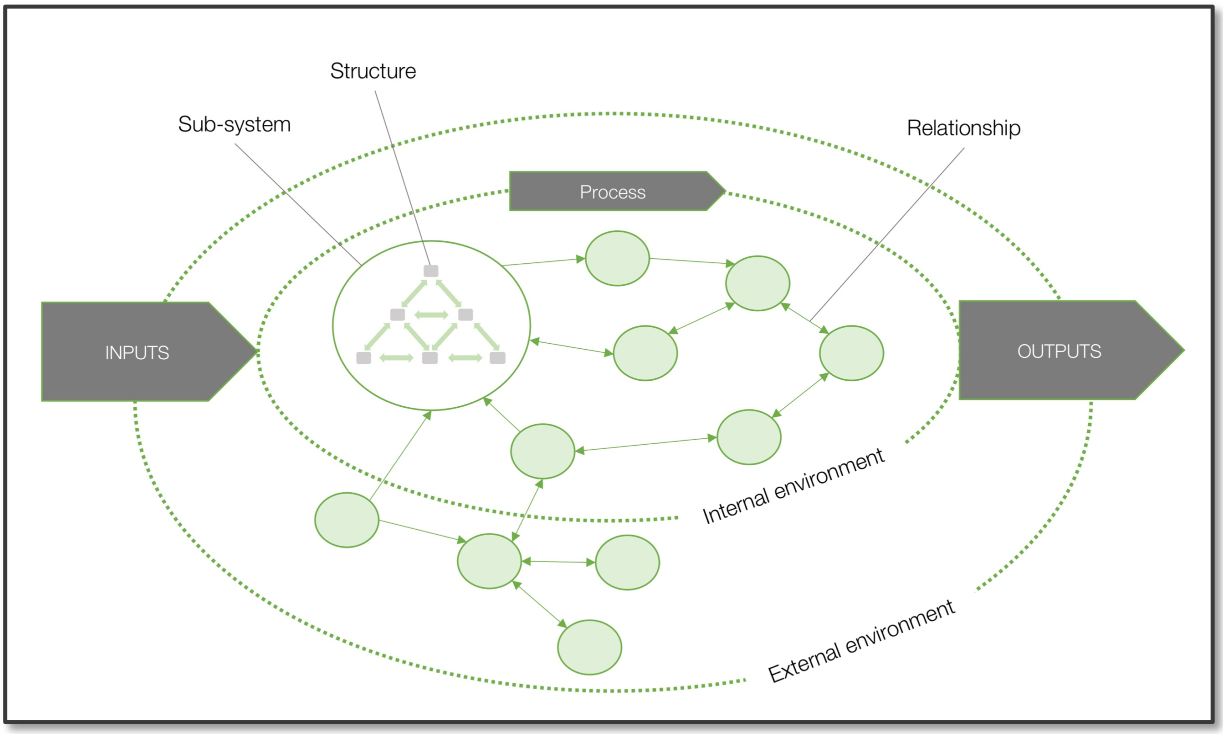


Figure 2.2: Von Bertalanffy's General Systems Theory (adapted from Jackson, 2003)

As indicated in Figure 2.2, a system implies a complex structure that extends into both the internal and external environment. During this process, various subsystems will emerge and interact that themselves in turn consist of structures. A subsystem may furthermore attempt to integrate and coordinate with internal and external structures. In this study, I accordingly viewed each group of participants as a cognitive system from an open perspective, which links to the ontological assumptions of my selected epistemological paradigm, being critical realism (refer to Chapter 3). This implied that I could not control the participants' interactions with the social, conceptual or physical structures in the cognitive system, neither did I have control over the cognitive events that emerged as a result of the participants' interactions with the various structures.

As indicated earlier, Von Bertalanffy (1950) distinguishes between closed and open systems. Whereas a closed system does not imply any exchanges with the environment, open systems, such as human beings, interact with the environment to sustain existence. Open systems can receive input from the environment, transform the messages and then place these as output back into the environment. Systems will, as a result, adapt in reaction to changes in the environment.

In agreement with this principle and the current Cognitive Psychology Theory (Heersmink & Knight, 2018; Menary, 2010; Walter, 2014), I view cognitive systems as open with the possibility of extending beyond the mind into the physical and social environment. The extended nature of cognition implies that when learners engage in designing, the dynamics between internal and external information sources will shape the way in which they solve design problems. As few cognitive and learning theories focus on the systemic and dynamic nature of learners' internal and external worlds (diSessa et al., 2016; Hall & Stevens, 2016), the manner in which teachers teach design problem solving does not always align with theory or recent research in this field. Limited existing studies report on the ontological nature of learners' real world problem solving activities (Haupt, 2018a), thereby once again emphasising the potential value of this study – not only for theory building but also due to the potential practical application value for teachers in the profession.

In summary, I regard the General Systems Theory of Von Bertalanffy (1950) as suitable to apply in this study for two reasons. Firstly, this generic systems meta-theory allowed me to study the systemic nature of the participants' engagement in their STEM tasks. By viewing their engagement in the cognitive system from a critical realist stance, I could study the various structures, mechanisms, and events that composed and emerged from the system (Bygstad, Munkvold, & Volkoff, 2016; Wynn & Williams, 2012). Secondly, the generic nature of General Systems Theory allowed me to situate the problem solving frameworks of Extended Cognition (refer to Section 2.5.3) and Activity Systems Theory (Section 2.5.4) within its meta-theoretical assumptions. In the following sections, I elaborate on the way in which I combined extended cognitive systems with General Systems Theory.

2.5.3 Development of the Extended Cognitive Systems Theory

In contrast to traditional theories of design, Extended Cognitive Systems Theory acknowledges the principle that learners' task environments encompass social, conceptual and physical structures (Haupt, 2015). Extended cognition developed as a subset of situated cognition (Carter, Clark, Kallestrup, Palermos & Pritchard, 2018; Robbins & Aydede, 2009) and distributed cognition theories (Hutchins, 2014). It draws on the extended mind thesis (Clark, 2006, 2008; Clark & Chalmers, 1998), which rejects exclusive internalist and externalist theories of cognition in favour of an integrated model of cognition (Menary, 2007, 2010). In essence, an extended cognitive system can thus account for a learner's developing interaction between perceivable information on the material characteristics of objects, people and contexts in the learner's physical environment, social activities between learners and other people, and their use of personal and STEM knowledge and skills during a task.

According to Sutton (2010), Extended Cognition Theory evolved as a result of at least two movements. The first movement relates to Clark and Chalmers's (1998) parity principle, stating that a cognitive process will be extended when an external part of the world functions in a way similar to that of a clearly recognised internal cognitive process. For studies on cognition, this implies that cognitive extension can be acknowledged when researchers establish similarities between internal and external states and processes.

However, the parity principle downplays the differences between internal and external cognitive states and processes, implying that the nature and properties of the external environment and its impact on the way people think and behave is not fully recognised (Heersmink, 2016). Furthermore, the principle does not acknowledge the individual differences between learners sufficiently, or how such differences may determine how learners interact with each other and their environments (Heersmink, 2016). These limitations of the parity principle resulted in my decision not to apply this principle in my study, but to rather adopt the second movement, which is based on the so-called complementarity principle as advocated by Menary (2007), Clark (2008), as well as Sutton (2010).

According to this movement, the external environment does not require similar functions as internal states and processes, but may complement internal processes with different properties and functionalities. In this regard, Menary (2007) explains that internal states and processes cannot be the same as external states and processes because the different functionalities inherent in internal and external structures provide the exact grounds for cognitive extension. So, for example, when complementing brain functions with external structures, the brain may be able to perform functions that it cannot do as efficiently on its own. As such, the brain, in combination with the external environment, can be seen as much more versatile and a more powerful cognitive or problem solving system than the brain alone. As I aimed to understand the interplay between the participants' use of internal and external information sources, I applied the complementarity principle in understanding this study. I elaborate on this principle in Section 2.5.3.2.

At its core, Extended Cognition Theory explains the nature and location of mental states from a systemic point of view, emphasising a functionalist understanding of mental states (Sprevak, 2009; Wheeler, 2010). This means that when I studied the design moves of the participating learners, I could only do so in relation to mental states' roles in completing cognitive tasks. I was furthermore able to determine the functional role of the identified design moves in terms of their causal relations to interactions in the physical and social environment, other mental states, and overt behaviour during the participants' completion of the STEM task. Furthermore, these design moves and their causal relations to internal and external structures and events were captured in the external representations of the participants. From an extended cognitive viewpoint, such representations are referred to as cognitive vehicles (Menary, 2007; Shani, 2013).

2.5.3.1 Cognition and extended cognition

According to the cognitivist framework, cognitive processes imply a system where input information is represented symbolically, which is then syntactically processed according to stored knowledge in the memory, into output behaviour. This view proposes a single, mental layer of cognitive processing involving input, processing, and output (Hurley, 2010). The theoretical framework of extended cognition however proposes multiple cognitive layers (Menary, 2015) within a dynamic systems approach. In these layers, multiple mental, bodily, and environmental processes are seen to contribute to cognitive task completion. Extended cognition therefore recognises the distinct processing layers of the brain, body, and environment (Menary, 2015).

For cognitivists, cognitive processing involves a causal sequence of thoughts (e.g. A → B → C → D), which allows for incremental syntactic processing. This means that each thought is viewed as a symbol token and that each antecedent token is causally responsible for a consequent token. In order to access thoughts, researchers will accordingly study a problem solver's external representations, or vehicles of thought, in which thoughts are instantiated. Such external representations include, for example, utterances, written notes, drawings and 3D modelling.

Extended cognition proponents believe that thought tokens have a causal influence over one another. As such, the notion that these tokens are only located in the mind of the problem solver is rejected. Proponents of extended cognition believe that the causal sequencing of thoughts is caused and formed by internal and external structures, which then form an integrated cognitive system. This integrated system is seen as the product of a problem solver linked to an external entity with two-way interaction, thereby creating a coupled system that can be regarded as a cognitive system in its own right (Clark & Chalmers, 1998). As a result, a problem solver's brain will perform some mental operations, while other physical operations will be delegated to the material and social environment – all contributing to the completion of the cognitive task.

It follows that extended cognition views any cognitive system as a dynamic system (Menary, 2015; van Gelder, 1995), being composed of parts that interact with one another where a change in one part will depend on the state of the other parts (Menary, 2015). Figure 2.3 illustrates an extended cognitive system as a dynamic system, with the wider system consisting of the mind, problem solver and environment. These three systems are linked as a result of continuous interactions of sensory and motor functions. According to Menary (2007), global properties and behaviours that arise from the interactions between these three systems can only be understood if the systems are viewed as part of a wider dynamic system, as these properties and behaviours are beyond the scope of a single sub-system. This implies that interaction between the systems is required for a cognitive task to be completed (Cooke, Gorman, Myers, & Duran, 2013; Favela & Martin, 2017; Menary, 2007).

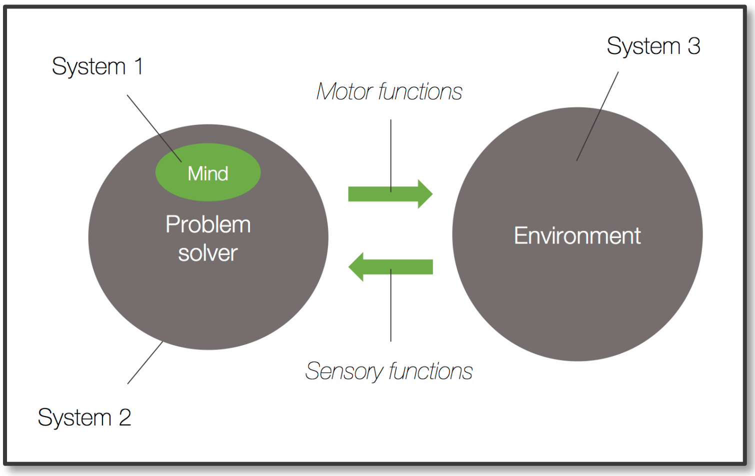


Figure 2.3: An extended cognitive system as a dynamic system

Focusing on the role of the external environment in constituting and driving cognitive processes can also be explained from the philosophy of active externalism (Arnau, Ayala, & Sturum, 2014; Clark & Chalmers, 1998; Hurley, 2010) whereby cognitive processing is constituted through active features of the environment. In this regard, Menary (2010) explains that active externalism entails a constitutive thesis rather than a mere causal one. The central idea in the initial conceptualisation of extended cognition relates to individuals using structures from the environment, including artefacts such as smartphones, computers or pencil and paper, where interaction between the problem solver and such artefacts may result in a coupled system that functions as a cognitive system. In other words, the external structures to which learners in a problem solving context are connected are seen as not only causally linked to cognitive processes, but also interactively linked to external structures, with this link having a causal influence on the cognitive processing of the problem solver (Menary, 2010).

Extended cognition rejects the idea of thought components being located exclusively within the body of the person performing a cognitive task. Instead, proponents of extended cognition argue that cognitive processes and cognitive vehicles extend beyond the body into the external environment (Menary & Gillet, 2017). As such, extended cognition frameworks acknowledge the processing of mental states and internal vehicles, but integrate the interactions of the problem solver with the environment, for example, when a learner uses pen and paper to solve a mathematical problem.

2.5.3.2 Basic principles of extended cognition

Extended cognition relies on three basic principles, namely complementarity, integration and manipulation. In explaining the complementarity principle, Sutton (2010, p. 194) states the following:

> *"In extended cognitive systems, external states and processes need not mimic or replicate the formats, dynamics, or functions of inner states and processes. Rather, different components of the overall (enduring or temporary) systems can play quite different roles and have different properties while coupling in collective and complementary contributions to flexible thinking and acting".*

According to Sutton (2010), cognitive systems can thus be regarded as assemblies in which problem solvers interact with various internal and external structures that collectively contribute to the completion of cognitive tasks. The properties of individual structures in the cognitive system are important in understanding how the cognitive whole functions. Another point that Sutton (2010) emphasises is that with the integration of external structures into a cognitive system, the system will transform its inner structures.

Menary (2010) elaborates on Sutton's (2010) work in describing the second basic principle of extended cognition, namely integration. Menary (2010) explains that extended cognition is based on cognitive integration, which emphasises the coordinated processes between problem solvers and their environments. The central principle of cognitive integration implies that cognition can be viewed as the coordination of the body with salient features of the environment. This coordinated process can allow problem solvers to perform cognitive tasks that they otherwise would not be able to do; or allow them to solve problems in ways that are different and better than those used when performing tasks *via* neural processes only (Menary, 2010).

Menary (2010) further argues that by focusing on the cognitive integration of internal and external cognitive processes and vehicles, researchers can avoid the criticisms of the Extended Mind Theory as they can then focus on the complementarity principle of active externalism (Menary, 2010). According to Menary (2010), integration can be conceptualised in three complementary ways. First, cognitive integration can be understood as biocausal coupling, which implies a symmetrical relation between a problem solver and some external structure, with a causal influence over one another as long as the coupled system exists. Second, cognitive integration can be understood as embodied engagement, which focuses on the way in which sensory and motor schemas for action couple the problem solver and environment. Thirdly, cognitive integration can also be understood in terms of Menary's (2010) manipulation thesis, which forms the third basic principle of extended cognition.

According to Rowlands' (1999, p. 23), "cognitive processes are not located exclusively in the skin of cognising organisms because such processes are, in part, made up of physical or bodily manipulation of structures in the environments of such organisms". Menary and Gillet (2017) elaborate by indicating six types of manipulations that may be utilised, namely biological coupling, corrective practices, epistemic practices, epistemic tools, representational systems, and blended practices.

Biological coupling refers to the direct sensory-motor interactions of learners with the environment, which are facilitated by means of simple perception-action mechanisms where direct perceptual input from the environment reciprocally causes action, which then directly feeds into further perception and more action. For example, during designing, learners are biologically coupled with external information sources such as sketches, where each mark made on paper may facilitate further thoughts and action. Corrective practices relate to learners' abilities to correct their own thinking and doing while working in the environment. Learners can use any cognitive vehicle as a corrective tool, and say, for example, "that didn't work, so I'll try this" when using speech as a corrective tool and vehicle through which they can correct their activities. In this regard, corrective practices commonly occur during and as a result of verbal interactions with peers when learners are busy with a design task.

Next, epistemic practices relate to learners' actions that may simplify cognitive processing by using the environment. Learners can, for example, use rulers, calculators, pen and paper activities, and computers to augment their cognitive processing. Representational systems relate to the creation, maintenance and deployment of representations during complex cognitive tasks. For example, learners might use diagrams as part of the processing cycle, which can in turn result in the completion of a cognitive task (Menary, 2015; Rowlands, 2003). Finally, blended practices involve the combination of cognitive practices in cycles of processing. For example, during design problem solving, learners may call upon the manipulation of tools in conjunction with the use of notational systems to complete the cognitive task of generating a design idea. In the current study, the design problem solving events that I studied were embedded in the above-mentioned cognitive practices.

2.5.4 Activity Systems Theory

As already indicated, in traditional Cognitive Psychology, thinking used to be studied only at an individual level of analysis (Greeno & Engeström, 2014; Nathan & Sawyer, 2014) in terms of learners' mental processes and conceptual structures (Greeno & Engeström, 2014). Activity Systems Theory (Engeström, 1987, 2015a), however, provides an analytical framework for studying the learning and thinking processes of two or more people, for example, in a group or a classroom. This allows researchers to investigate the ways in which individuals act and interact with each other in a group and with material resources (Greeno & Engeström, 2014).

The underlying principles of Activity Systems Theory imply that social systems, such as organisations, will result from the intentions, motives or purposes that people have in a system (Jackson, 2003), which will in turn stem from the interpretations that they make of the situations they experience. From an Interpretivist Systems Theory paradigm, learners engaged in STEM tasks can thus be guided to seek an appropriate level of a shared connection-making culture in their learning groups.

2.5.4.1 First and second generation Activity Systems Theories

The founder of the first generation of Activity Systems Theory, Vygotsky (1978), believed that in order to understand learners' thinking processes, it was necessary to understand the whole context of interaction between learners and their social and material worlds (Engeström, 2015). Vygotsky's triangular model of mediation, captured in Figure 2.4, illustrates the major components of an activity system as conceptualised by this theorist.

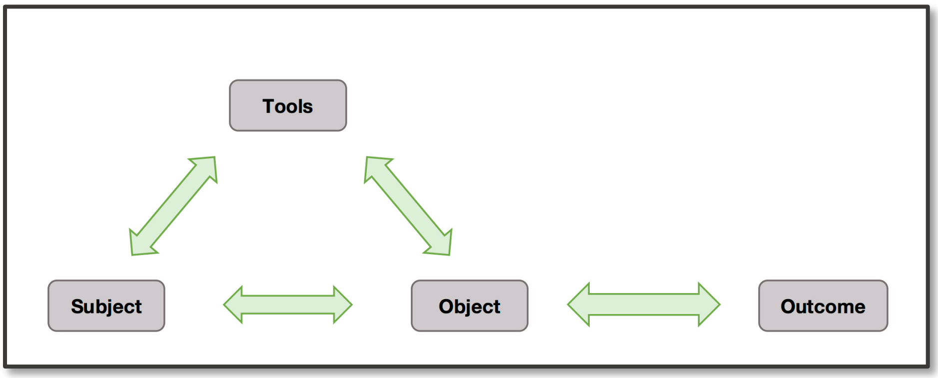


Figure 2.4: Vygotsky's triangular model of mediation and the transformation of an object into an outcome (Engeström, 2015)

As depicted in Figure 2.4, Vygotsky found the primary relationship in an activity system to be between subject, object and tools (Engeström, 2015). During the development of this first generation Activity Systems Theory, Vygotsky (1978) viewed a subject as an individual or the person engaging in an activity, and the object as that which the subject is interested in achieving – driving the activity or giving the activity its purpose. The mediation between a subject and an object is seen as being supported by a range of conceptual and physical tools. Based on Vygotsky's conceptualisation, I regarded the Grade 8 participants as the subjects in this study; their intentions to analyse the problem statement, creating the design brief, constraints, specification list, design sketches and 3D models of a design solution as the objects of the activity; the solving of the STEM task as the outcome; and the various internal and external information in the extended design task environment as the mediating tools to solve the STEM problem.

Whereas Vygotsky's first generation Activity Systems Theory only focused on individual activity, Leont'ev's (1978) theory captures an expanded view – acknowledging collective activity from three levels, namely activity, action and operation. The purpose of Leont'ev's (1978) three levels was to distinguish collective activity from individual actions and operations. At the level of activity, which is associated with intentional object-oriented activity, Leont'ev (1978) focused on *why* a collective activity would be performed. For example, in this study, the participants were guided by my instructions to analyse a problem statement, propose design constraints, write a design brief, create a specification list, generate design ideas and create a 3D model of their chosen design idea.

Secondly, for the level of action, Leont’ev focused on *what* individual and collective actions would be performed by each of the subjects. In this regard, I firstly had to analyse when each of the participants generated a design move by studying their external representations, including utterances, written notes, gestures, drawings and 3D modelling instances. Finally, at the level of operation, Leont’ev focused on *how* individual actions would be performed in order to contribute to a collective activity. In this study, after determining the sequence of design moves, I was able to code the participants’ design problem solving events in attempting to determine their interactions with conceptual, physical and social structures. At this level, I furthermore used mental and physical operators to microscopically analyse how each individual participant interacted with social, conceptual and physical structures in order to contribute to the collective activity. More detail about the process of analysis that I completed is included in Chapter 3.

In response to the limitations of Vygotsky’s first generation Activity Systems Theory, and taking Leont’ev's (1978) expansion to collective activity into consideration, Engeström (1987) developed a theory that allows for the examination of activity systems at the collective level in a community while still focusing on individual subjects too. Similar to Vygotsky and Leont’ev, Engeström views an activity system as object-oriented, mediated and collective in nature. Engeström thus developed his second generation Activity Systems Theory (Engeström, 2015) to allow researchers to observe the interactions between individuals and the physical environment, and how these interactions affect one another. Engeström’s second generation Activity Systems Theory is captured in Figure 2.5.

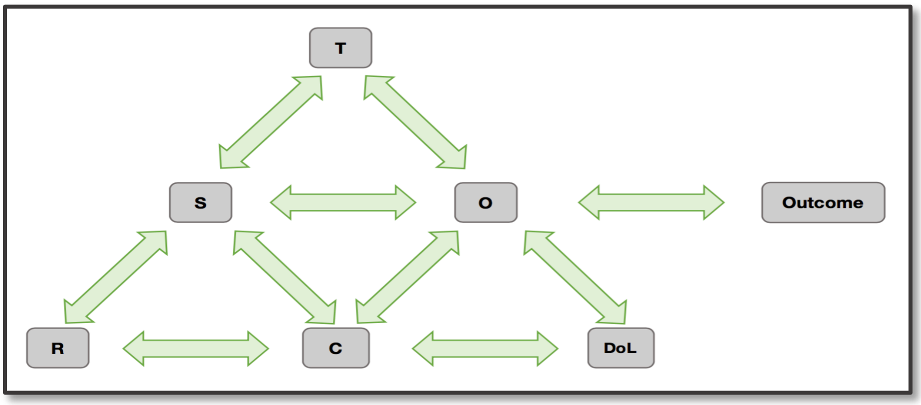


Figure 2.5: Engeström's (1987) second generation Activity Systems Theory

As illustrated in Figure 2.5, the main components of Engeström's Activity System Theory include the subject(s) (S), object (O) and outcome, as well as the mediators of the object-oriented activity, being the tools (T), rules (R), community (C), and division of labour (DoL). As in Vygotsky's first generation Activity Systems Theory, the subject of an activity system refers to the person or group of people who engage in an activity (Engeström, 2015). The object entails the intentions or goals of the activity system as a whole, for example, writing a design brief and generating ideas with sketches. Both the subject and object are seen as being constantly mediated by conceptual and physical tools, the nature of the community to which the activity system belongs, the rules of behaviour appropriate to the system, and the division of labour within the system (Engeström, 2015). The term 'division of labour' can refer both to hierarchical power structures within a system, or to the way in which labour is divided within the context of a system. In this study, this implied that rules and the division of labour determined how the participants were expected to behave and who was expected to do what in addressing the object of the activity system (Stevenson, 2004).

2.5.4.2 Underlying principles of Activity Systems Theory

Kaptelinin and Nardi (2006) propose five basic theoretical assumptions of Activity Systems Theory, which also apply to this study. First, *object-orientedness* rests on the belief that human activities are intentionally directed toward objects. When learners, for example, engage in STEM tasks, they are directed toward solving real-world design problems. In this case, objects are continuously generated as learners engage in problem solving activities, with such objects motivating and directing the activities of learners (Greeno & Engeström, 2014). In Figure 2.6, the interdependent relationship between subject, object and outcome in terms of the object-orientedness of the early phases of learners' STEM tasks is illustrated, thereby indicating my application of this principle in my study.

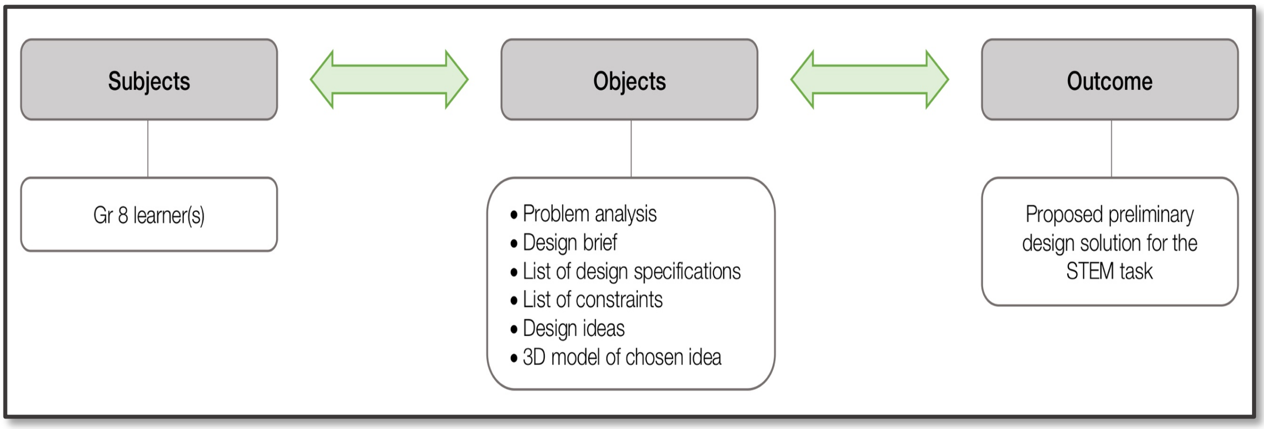


Figure 2.6: The object-orientedness of the early phases of a STEM task

I thus provided the participants (subjects) in this study with their STEM tasks expecting of them to engage in certain object-oriented activities such as analysing their design problem and creating a list of design specifications. These object-oriented activities influenced the way in which the subjects (Grade 8 learner participants) understood the STEM task, and how they developed the outcome, i.e. a proposed preliminary design solution for the STEM task. In essence, objects of activities relate to prospective outcomes that can direct subjects' activities (Engeström, 2015b; Kaptelinin & Nardi, 2006). The activities of subjects and their objects can in turn be crystallised in a final outcome when a subject's activities have been completed.

The second principle of Activity Systems Theory relates to *internalisation and externalisation*. Most object-oriented activities contain both internal and external structures (Engeström, 2015b; Kaptelinin & Nardi, 2006). Internalisation refers to the process by which conceptual tools, mental representations and schemas are created in the mind of a problem solving learner based on external activities. From an extended cognition viewpoint, the way in which a learner internalises a problem and solution depends on the tools in the social and physical environment (Hutchins, 2014; Menary & Gillet, 2017). Alternatively, externalisation refers to the process whereby internal ideas manifest in the external world (Menary & Gillet, 2017; Vygotsky, 1981), for example, in the form of utterances, gestures, drawings or note making. When externalised ideas are combined with learners' perceptual systems, it can result in changes in learners' internalisation, for example, their understanding of a design solution. Hence, the interaction between internalisations and externalisations that are facilitated by direct perception and action can be thought of as a "criss-cross brain, body, and world" process (Clark, 2008, p. 281). Schön (1983) describes this process as engagement in conversation with the world where the world 'talks back'. According to this view, the act of bringing thoughts into material form, such as expressing design ideas in sketches and 3D models, is not merely to make visible one's 'mental representations', but is itself constitutive of cognitive activity (Heersmink, 2017; Menary & Gillet, 2017).

Engeström (1987) believes that an activity that is distributed between several people, for example, triads of learners engaged in a STEM task, can be transitioned from the group to the individual. The opposite process involves the transformation of an individual activity into a socially distributed one (Cole & Engeström, 1993), for example, when one learner proposes a design idea and others join the learner to develop the design proposal. When an internal activity is externalised, it will also affect the individual/social dimension. For example, once an individual learner has externalised a sketch of a possible design solution, other group members can make adaptations based on their experiences, or evaluate the suitability of the design idea and develop the sketch to make a mock-up of their idea. Evaluating the suitability of the design solution may, in turn, trigger experiences with existing solutions, which falls into the internal-individual dimension. Of importance for this study was the transitions between internal and external dimensions, as well as between individual and the social dimension, as proposed by Leont'ev (1978). A difference between Activity Systems Theory and Haupt's (2016) Extended Design Cognition Theory is however that Activity Systems Theory does not focus on the ontological dimensions of thinking processes – it merely focuses on the methodological dimensions of thinking. As a result, I decided to combine Engeström's (2015) Activity Systems Theory with Haupt's (2015) Extended Design Cognition theory when undertaking my investigation.

The third principle of Activity Systems Theory involves *mediation*. In this study, I focused on tool mediation processes, which consist of conceptual and physical tools, as well as social mediation processes in order to describe the nature of the social interactions between the participants and how their interactions contributed to the problem solving activities of the STEM tasks. The term ‘tool’ includes physical tools that affect the material world, yet also conceptual and symbolic tools that may affect the mental world of an individual and the community. In a dual process, learners shape both their physical and social environments while being shaped themselves through the use of mediating tools. Internalisation implies the process by which conceptual tools, mental representations, and schemas are created in the mind of a problem solving learner based on his/her external activities. This means that learners’ internal worlds will necessarily form part of their physical learning environments. It follows that a learner will make meaning of the world through interactions with tools and other individuals in a particular environment.

Mediating tools may also be perceived as passive components in STEM learning environments (Chao et al., 2017) despite physical tools significantly influencing students’ psychological processes when performing cognitive tasks. The embodied knowledge in physical tools can mediate a user’s actions by implicitly specifying the modes of operation for the subjects (Norman, 1993; Vygotsky, 1981) as affordances. Through constant use, mediated actions can in turn gradually be internalised into mental processes and structures that can be used independently regardless of the presence of the tools. For example, the shape of a saw afford the action of sawing wood. With the repeated use of saws, learners may be able to visualise the process of sawing when using a saw, and develop the embodied schema of ‘sawing’ (Stevenson, 2004). As such, tools are not only instrumental to carry out tasks, but can also influence the way in which learners think and visualise future actions for STEM tasks.

In this way, tools can provide valuable feedback on the structure, functions, and behaviours of proposed design ideas during STEM tasks. For example, Apedoe and Schunn (2013) found in their study that students who engaged in iterative testing cycles with their physical modelling materials developed deeper understanding of quake-resistant structures. Tools may furthermore also mimic social mediation where learners shift their focus to conceptual understanding in support of meta-cognition. Experienced designers will accordingly engage in reflective conversations with design problems, frequently transitioning between understanding a problem (e.g. gathering information and determining constraints) and solving the problem (Atman et al., 2007). For learners, such reflection is critical when acquiring STEM concepts and skills.

Despite the importance of tools in design problem solving, the role of tools in STEM learning environments has not yet been researched widely due to the learning environments used in research often lacking a range of physical tools, such as construction and testing tools (Hmelo, Holton, & Kolodner, 2000; Shaffer & Clinton, 2006; Slangen, Van Keulen, & Gravemeijer, 2011). Even though physical tools have been recognised as important structures in design problem solving learning environments in various studies (Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005; Kolodner et al., 2003; Wendell & Lee, 2010), the exact nature of student learning often remains implicit and ambiguous, and may not immediately be connected to STEM knowledge and skills in the classrooms.

In a study on the way in which learners think in a robotics environment, Sullivan (2008), however, found that learners' understanding of systems significantly improved after their interactions with tools during the design task. Sullivan (2008) links learning to the nature of the tools available in the classroom, which can provide immediate feedback and motivate learners to iteratively improve their design solutions. Kim, Suh and Song (2015) similarly attribute learning to the nature of the tools provided in the learning environment. As the effect of available tools can be confounded by the social mediation of teachers in the STEM environment (Fortus et al., 2005; Puntambekar & Kolodner, 2005; Wendell & Lee, 2010), I decided to observe the participants' interactions with tools in this study, including minimal guidance from their teachers.

In addition to tool mediation, external representations can become available not only to the learner who generate these, but also publicly to other members of a learning community. In this way, problem solving can be thought of as being 'distributed across' other people with external representations mediating socially coordinated cognitive activity – so-called social mediation. A number of researchers (Barlex & Trebell, 2008; Hamilton, 2008; Murphy & Hennessy, 2001; Trebell, 2009) therefore regard the nature of STEM activities as social activities drawing on interactions between pupils as well as pupils and the teacher. Such a view of learning as a socially mediated activity draws on the work of Vygotsky (1978, p.90), who believes that "Learning awakens a variety of internal development processes that are able to operate only when the child is interacting with people in his environment and in co-operation with their peers". According to Vygotsky (1978), all higher mental processes are mediated by psychological tools such as language, signs, concepts and symbols. However, ongoing research is required on the ways in which these tools can support STEM problem solving activities in the classroom.

As previously indicated, Engeström (1987) expanded on the work of Vygotsky (1978) and Leont'ev (1978) by extending object-oriented activity to collective activity in adding a third node, 'community', which comprises other members of the team such as other learners, the teacher and even parents. As such, Engeström (1987) highlighted the role of social mediation during activity, and captured how each of the three interactions within his structure can be mediated. Mediational means for these interactions include tools for the 'subject-object' interaction, rules for the 'subject-community' interaction, and division of labour for the 'community-object' interaction.

The last theoretical assumption of Activity Systems Theory relates to the importance of *activities always being analysed in the context of development* (Engeström, 2015), with development referring to both an object of study and a research strategy. In this study, I set out to study the incremental development of the participants' thought processes (object) as they engaged with various conceptual and physical tools during design problem solving. As such, I mapped the physical and mental operations that contributed to emerging individual and collective design moves (research strategy), which in turn contributed to the emerging design object-oriented activities of the participants. In conclusion, the principles of Activity Systems Theory comprise an integrated system that represents different aspects of human activity as a whole. The systematic application of any one of the mentioned principles as a result necessitates the engagement of other principles too.

2.6 CONCEPTUAL FRAMEWORK OF THE STUDY

I compiled a conceptual framework for this study by integrating the work of Haupt (2015), who developed her theory of Extended Design Cognition from Goel and Pirolli's (1992) Information Processing Theory of Designing, while integrating principles from Ecological Psychology (Anderson, 2003); as well as the Activity Systems Theoretical perspectives of Engeström (2015). In compiling the conceptual framework, I attempted to create a structure that could guide me in exploring, describing and explaining the structures and mechanisms underlying learners' design problem solving events. As such, my conceptual framework can be described in terms of three theoretical components as summarised in Table 2.1.

Table 2.1: Conceptual framework comprising three theoretical components

Theoretical component	Theoretical assumption
Extended information processing system (Haupt, 2015).	Design problem solving is dependent on input information about a problem situation, or opportunities that are systematically transformed during a transformation process into a physically embodied solution output, which might take the shape of 3D models, drawings or a physical artefact.
Extended problem solving space (Haupt, 2015; Engeström, 2015).	Designing is seen as a goal-directed search process in an ill-structured problem space. The extended problem space contains a team of designers' knowledge of the initial problem state, a goal state, and all the possible design states between these two states. Designing can accordingly be viewed as a sequence of state transformations, beginning with the start state, proceeding through mediating states, until a final goal state is reached. Each state can furthermore be described in terms of an activity system, consisting of a subject, object, tools, rules, community and division of labour.
Extended design task environment (Haupt, 2015).	The extended design task environment contains the given problem statement and any other internal and external information sources that can assist a team of designers to solve a design problem.

The way in which I integrated these theoretical components and concepts from existing theory is captured in Figure 2.7. In explaining my conceptual framework, I first discuss each of the theoretical components individually, after which I explain how I related the various components to each other for the purpose of this study.

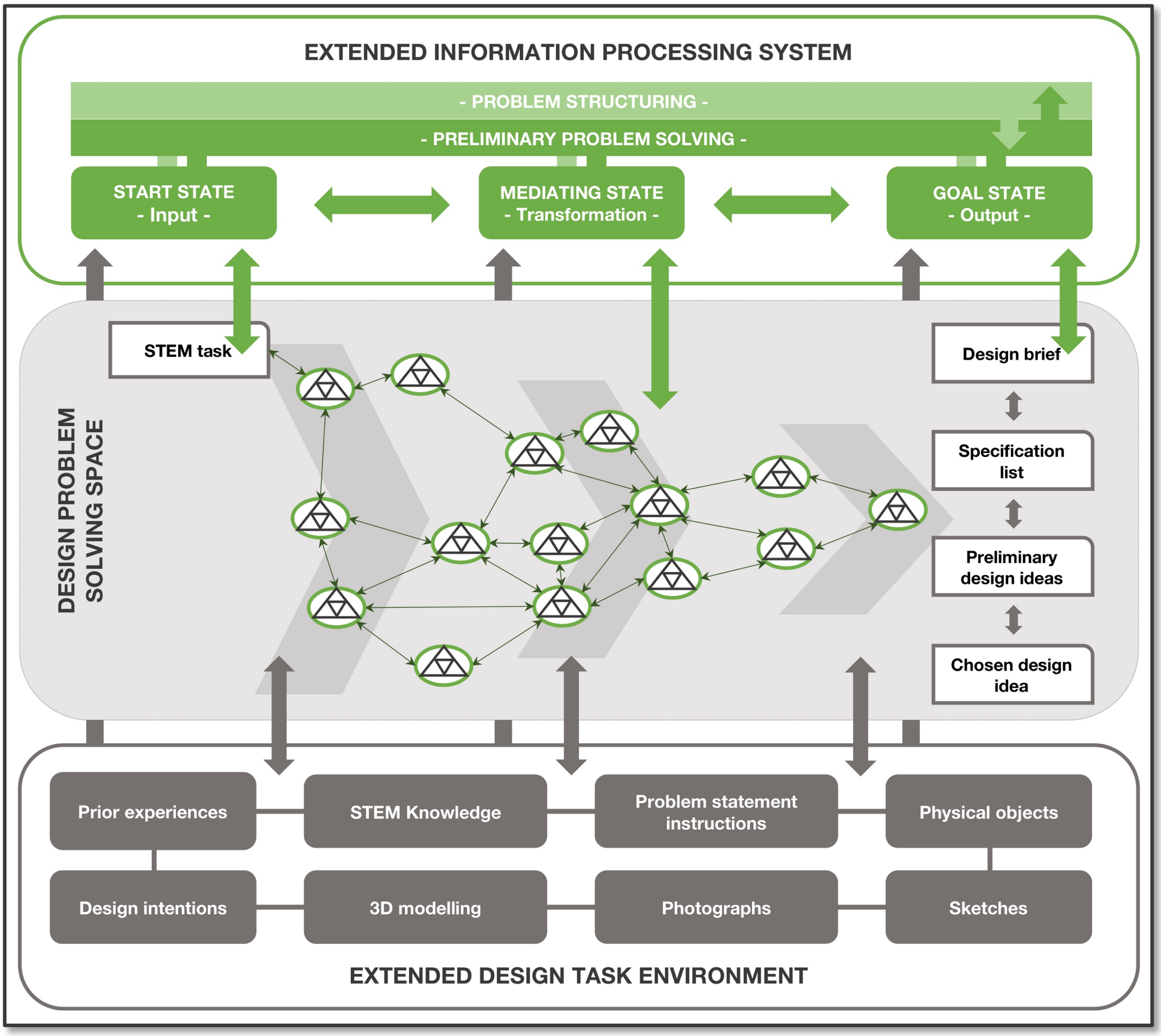


Figure 2.7: Conceptual framework (adapted from Haupt [2015] and Engeström, [2015])

2.6.1 Extended Information Processing Theory

According to Newell and Simon (1972), when human beings solve design problems, these can be represented as information processing systems. In their empirical investigation of expert designers during the early phases of the design process, Goel and Pirolli (1992) as well as Haupt (2015) regarded the information processing system as a group of designers facing a problem. The extended information processing system (Haupt, 2015) consists of three structures, namely input, process and output. The descriptive power of the extended information processor lies in the assumption that problem solving is dependent on abstract input information sources regarding a problem situation and design intentions, which is systematically transformed during a transformation process into a physically embodied solution output (Goldschmidt, 2013).

In this study, I only focused on the first two phases of designing, constituting the early phases of the design process, being problem structuring and preliminary problem solving (Goel, 1995; Haupt, 2015). Problem structuring refers to the psychological process of forming a mental, subjective representation that reflects the perceived problem state and desired outcome (Simon, 1973). Typical activities in the design process related to problem structuring include defining the problem to be solved by understanding the user's needs and the design context; proposing and modifying design requirements, limitations and constraints; and formulating design goals and sub-goals (Björklund, 2013; Dym et al., 2014; Hay et al., 2017). Preliminary problem solving refers to the psychological process of 'searching' for possible solutions in a design problem solving space (Simon, 1973). Typical activities in the design process related to problem solving include proposing alternative design ideas, elaborating on possible design ideas, and choosing design ideas that could be developed further into a final design specification (Dym et al., 2014; Goel, 2014).

2.6.2 Extended problem solving space

Each of the structures included in the Information Processing Theory corresponds to problem solvers' psychological states. Design researchers, however, acknowledge that the psychological states in design problem solving can be characterised by a lack of information due to the ill-defined and ill-structured nature of design problems (Goel, 2014; Haupt, 2018b; Hay et al., 2017). Yet, psychological states will determine the construction and boundaries of a problem solving space. The psychological states that make up the problem solving space can be distinguished as the start, mediating and goal states; these as captured in Figure 2.8.

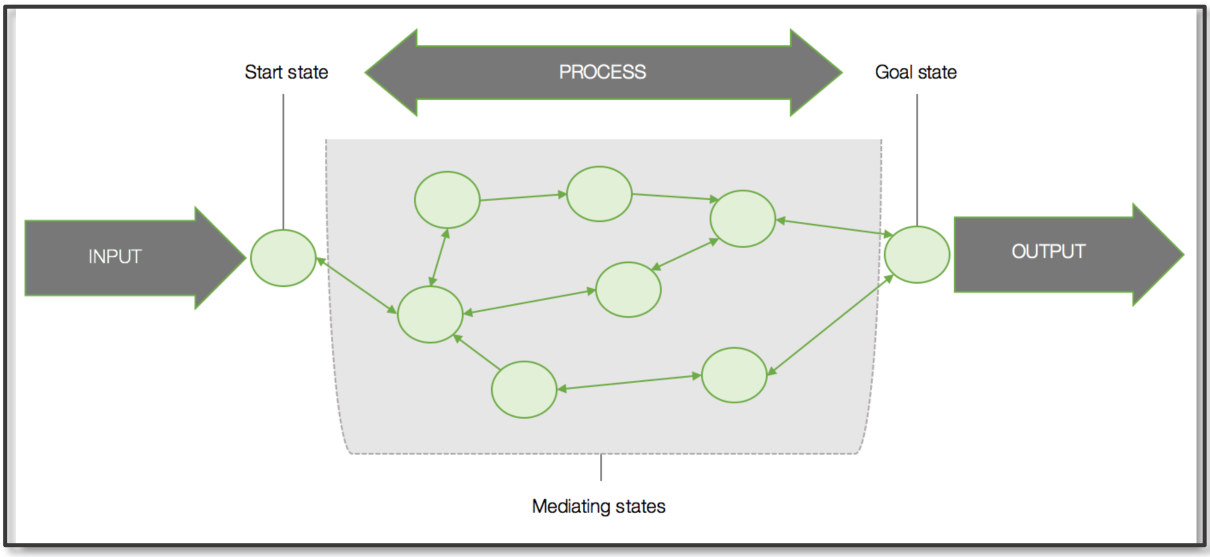


Figure 2.8: Extended Design Problem Solving Space Theory

The *start state* represents the psychological state where learners receive STEM tasks for the first time (Haupt, 2015; Newell & Simon, 1972; Reed, 2016). At this stage, they will experience uncertainty due to the ill-structured and ill-defined nature of the task, based on limited information about the problem and limited knowledge and information of possible solutions. This will require the participants' engagement in a cognitive process of understanding the problem or finding solutions in the mediating states.

The *mediating states* represent the psychological states in which the dynamics between learners' understanding of their STEM task, and their choice of a suitable solution to the problem unfold (Haupt, 2015; Newell & Simon, 1972; Reed, 2016). These dynamics are caused by the limited information contained in each mental state, and the learners' need to know. It is during the mediating states that learners will typically interact with various social, conceptual and physical structures, as exemplified in the Activity Systems Theory (discussed in Section 2.5.4), in order to develop suitable output solutions. These interactions include those between the subjects, object and community, which are mediated by tools, rules and division of labour.

The *goal state* represents the psychological state where learners have successfully solved a STEM task by choosing a suitable design solution (Haupt, 2015; Newell & Simon, 1972; Reed, 2016). During the start and mediating states, the goal state is ill-defined. As learners progress with the problem solving task, they will make design choices that will typically result in the narrowing of the problem space. This means that in the beginning of the design process, learners will have a vague and abstract idea of the problem and solution. While they engage with social, conceptual and physical structures, they can explore the problem space in order to structure their problem, manage the process and find a solution (Goel, 2014; Haupt, 2015; Ullman, 2009). The goal state thus represents a defined solution that may address an ill-structured problem in the start state. The solution might be embodied in the students' design briefs, specification lists, idea sketches, and 3D models.

2.6.3 Extended Design Task Environment Theory

In order to guide their problem solving during a STEM task, learners need to access a variety of available internal and external information sources in the extended design task environment (Haupt, 2015). Internal sources relate to information stored in learners' memory and information that is related to the STEM task, whereas external information sources include information perceived from the learners' physical environment through sources such as drawings, textbooks, 3D modelling materials, manufacturing tools, and pictorial information.

I made a distinction in this study between knowledge and information. On the one hand, I viewed knowledge through the lens of Conventional Information Processing Theory as the representations of knowledge internally stored and processed in the participants' minds and memories (Rodgers & Clarkson, 1998). This included conceptual knowledge, procedural knowledge, and visualisation (Section 2.3.2.3) On the other hand, I viewed information through the lens of extended cognition, as structures contained in the external environment with which learners could interact and manipulate (Logan & Radcliffe, 2007; Menary & Gillet, 2017; Rodgers & Clarkson, 1998). As such, I viewed the participating learners not only as information processors, but also as information detectors, as suggested by Ecological Psychology (Young, 2004).

Ecological Psychology Theories namely state that cognition emerges when learners perceive information specified in the material environment, and consequently take action thereupon (perception-action) (Young, 2004). Perception-action implies that the physical and social interaction of learners within the extended design task environments will become the basic unit of analysis.

In the learning environment, learners are viewed as intentionally-driven information detectors who are able to detect a wide range of information from their environments. In this regard, Ecological Psychology assumes the dynamics of intentions and intentional dynamics of learners during designing (Haupt, 2015; Young, 2004). The dynamics of intentions refer to the fact that learners are intentionally driven during problem solving and will generate multiple design intentions as a result of their interactions with the physical and social environment (Young, 2004). These generated intentions will furthermore guide what learners pay attention to within the physical and social environments. It follows that, intentional dynamics refer to how learners attend to external information as they work towards a specific goal or intention (intention-attention) (Young, 2004).

When interacting with external information within an extended task environment, learners use direct perception (Young, 2004). In his ecological approach to visual perception, Gibson (1986) explains that information exists in the physical environment that is directly available to the perceiver, and does not need to be recalled from the long-term memory. In order to describe the functional value of information in the environment, Gibson (1986) introduces the concept of 'affordances' to explain how the detection of information in the physical environment provides opportunities for action. According to Gibson (1986), affordances are possibilities for actions that arise out of an opportunity for two compatible systems to interact in a particular fashion. Although the concept of affordances was not initially conceived to be used in learning environments, it has become an important concept in the design of learning environments (Barab & Roth, 2006; Young, 2004).

2.6.4 Applying my conceptual framework to the current study

In applying the Extended Information Processing Theory to this study, I considered a group of three Grade 8 learner participants who had to complete a STEM task as an information processing system, capable of solving a design problem; with the given STEM task being the input information. As the given task was ill-structured, it had to be transformed by the participants in order for them to identify the design problem, requirements, constraints and possible solutions from which they could choose and subsequently develop. Finally, I regarded their chosen solution as the solution output, which was represented in their sketches, written notes and 3D models.

As the role of teamwork and social activities in design problem solving processes is still being researched on an ongoing basis (Gweon et al., 2017; Marra et al., 2016; Toh & Miller, 2015), I decided to expand on Haupt's (2015) extended design cognition framework, by including Engestrom's (2015) social aspects of activity systems. In order to investigate these social aspects of an activity system, I used Jiang and Gero's (2017) notion of intragroup communication where I studied how the participants either transformed their own thoughts or each other's thoughts during the intermediate states in the problem solving space.

Against the background of the Extended Design Problem Solving Space Theory, I focused on learners' interactions with social, conceptual and physical structures, which brought forth intermediate states from which I could study the emergent design problem solving events. The implication of using a Problem Solving Space Theory is that it provided me with a systematic, linear and regimented framework for analysing the micro development of learners' thought processes during STEM activities. In this regard, I was able to rely on linkography to study the incremental emergence of mediating states, or design moves, during learners' design activities. Having the sequence of design moves made it possible for me to establish the links between the thoughts that emerged during designing as a result of the underlying social, conceptual and physical structures with which the learners interacted.

The implication of using the Extended Design Task Environment Theory (Haupt, 2015) is thus that I was able to investigate how learners detected the functionally defined informational-specified properties of their worlds (Young, 2004). Learners will typically do this to compensate for the ill-structured nature of a design problem. While the participants in this study were engaging in the given STEM task, I attempted to understand how they interacted and gained information from the social and physical structures in their extended task environment in order to identify the information that they needed to solve their design problem. To this end, the concept of 'affordances' implied that the way in which learners used information from the environment could not only be understood by studying the verbal utterances of the participants alone, but by also examining the relationship between learners and their interactions in the extended design task environments. I specifically focused on how the participants visually detected information in their physical environment with which they were able to interact. Gibson (1982, pp. 404–406) suggests that a perceiver will detect functional information from various visual elements, such as shape, form, size, colour, texture, line, proportion, weight, position, motion, surface layout, substance and lighting.

2.7 CONCLUSION

In this chapter I explored the existing literature on my focus of interest as background to my understanding of the underlying structures and mechanisms of learners' design problem solving events. After rooting my study in the philosophy of technology, I explored learners' design problem solving from a Systems Theory perspective by emphasising a combination of Extended Cognition and Activity System Theory as a lens to examine learners' design cognition.

In the next chapter, I discuss the methodological choices that I made in conducting this study. I describe the critical realist stance that I took and the multiple case study research design I implemented. I explain the data generation, documentation, analysis and interpretation procedures, as well as the quality measures that I employed to ensure ethical research in a rigorous manner.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

In the previous chapter I discussed the theoretical underpinnings pertaining to this study. This theoretical foundation provided a basis for the way in which I planned and conducted my study. In this chapter, I explain the methodological choices I made to achieve the purpose of this study. I provide an overview of the selected research paradigm and justify my selected research approach, research design, as well as the data generation, documentation, analysis and interpretation procedures. I conclude the chapter by discussing the quality measures that I subscribed to and the ethical principles I adhered to in undertaking this study.

3.2 EPISTEMOLOGICAL PARADIGM

Research paradigms are constituted by a range of philosophical assumptions that guide researchers' ways of thinking about the phenomena they investigate, as well as the actions they employ (Creswell & Plano Clark, 2018). In order to best address the research questions and purpose of this study, I took a critical realist stance. I support the views of Bhaskar (1998) that critical realism is primarily a paradigm concerned with ontology.

Ontology captures the assumptions that I made about the nature of reality, of what exists and does not exist (Danermark et al., 2002; O'Mahoney & Vincent, 2014; Sayer, 2010). The ontological assumptions are important when doing research as these will in turn affect epistemological assumptions and the knowledge claims that are made (Danermark et al., 2002; O'Mahoney & Vincent, 2014; Sayer, 2010). My epistemological assumptions were similarly related to my beliefs about how the reality I believe exists could be studied and better understood (Danermark et al., 2002; O'Mahoney & Vincent, 2014; Sayer, 2010).

Critical realism is a relatively new paradigm that emerged during the 1970s. The underlying framework was initially introduced by Roy Bhaskar (1975), and then further explained, refined and extended by a number of other scholars (Archer, 1995; Danermark et al., 2002; Sayer, 2010). For the purpose of this study, I focused on the foundational concepts originally presented in the seminal works of Bhaskar (1975, 1998), which contain the essential elements of critical realism that I was able to use to derive causal explanations of the participants' design cognition without introducing the complexities of additional philosophical, metaphysical and axiological issues.

According to critical realism, the ontological world, i.e. external reality, which exists independently of people's knowledge of it, differs from the epistemological world, i.e. the knowledge structures that people possess, which is socially constructed. Essentially, critical realism is based on two philosophical positions related to ontological realism and epistemological relativism. Ontological realism assumes that the external reality exists independent of its social construction. In this regard, physical and psychological structures and mechanisms can be identified that have properties that are not socially constructed or subjective in nature. In terms of epistemological relativism, researchers' knowledge of the ontological world is seen as limited, subjective and socially constructed. This implies that the representations of reality within a researcher's mind are partial and imperfect, but that these understandings will approximate with varying degrees of specificity and faithfulness.

The above-mentioned positions reflect an ongoing debate on critical realism as an alternative research paradigm to traditional philosophies. On the one hand, critical realism acknowledges that an objective world exists that is independent of the existing knowledge or perceptions thereof (O'Mahoney & Vincent, 2014). On the other hand, critical realism states that part of reality consists of subjective interpretations that will inevitably influence the ways in which reality is perceived and experienced (O'Mahoney & Vincent, 2014). This seemingly two-sided acknowledgement of a simultaneously objective and subjective reality represents a relatively new worldview within social science research (Teddlie & Tashakkori, 2009). In the following sections, I discuss the underlying assumptions of critical realism, and then reflect on my rationale for choosing this paradigm, as well as the challenges I faced due to this decision.

3.2.1 Ontological assumptions of critical realism

Ontologically, critical realism assumes an independent reality, a stratified ontology, and an open systems perspective (Bhaskar, 1975; Bygstad et al., 2016; Wynn & Williams, 2012). The assumption of independent reality is based on the idea that reality exists independent of the knowledge that a researcher holds. This implies independent internal and external structures despite peoples' perceptions of such structures. The existence of these structures are knowable in two domains, namely an intransitive domain and a transitive domain (Bhaskar, 1975, 1998). Structures in the intransitive domain can be empirically observed and experienced by researchers, while structures in the transitive domain cannot be directly observed, but only seen by means of theoretical frameworks.

In my study, this assumption confirmed the presence of internal psychological as well as external physical and social structures that I was able to study through a critical realist lens. The external structures included the participants, the tools that they used, their external representations and their learning objects, which were all observable and could be video-recorded. Internal psychological structures and mechanisms entailed the participants' knowledge stored in memory and intention-attention mechanisms underlying the development of the participants' thoughts. These were not perceivable, resulting in my implementation of multiple theoretical frameworks to study the participants' design cognition processes.

According to the second ontological assumption of critical realism – stratified ontology – reality can be differentiated in terms of three ontological levels of existence, namely, the Real, the Actual and the Empirical (Bhaskar, 1975; Wynn & Williams, 2012). In critical realism, researchers investigate phenomena on all three of these interrelated levels of reality. First, the real level consists of independently existing social, conceptual and physical structures that may have causal capacities or not. Structures that are causal are called 'mechanisms' if they possess the capacity to cause events on the ontological level of the actual (Bhaskar, 1998). This means that, in the domain of the real, researchers will typically study structures and mechanisms that may cause events on the actual (second) level.

As such, the actual level consists of observable and unobservable events that have been caused by the structures and mechanisms on the real level (Bhaskar, 1998). However, it is not possible to observe all events caused by mechanisms, for example, cognitive events. As a result, researchers may have to rely on theories and conceptual frameworks from the transitive domain to explicate and understand unobservable events (Bygstad et al., 2016; Danermark et al., 2002; Wynn & Williams, 2012).

Thirdly, the empirical level entails a subset of the real and actual levels and consists of the observable events that researchers are able to directly experience *via* perception or measurement. As such, the empirical level represents the ability to empirically experience events and mechanisms. In the current study, the empirical domain thus provided me with a starting point to examine the mechanisms underlying the learners' design cognition events. I provide an overview of my application of Bhaskar's (1975) ontological levels of reality in this study in Figure 3.1.

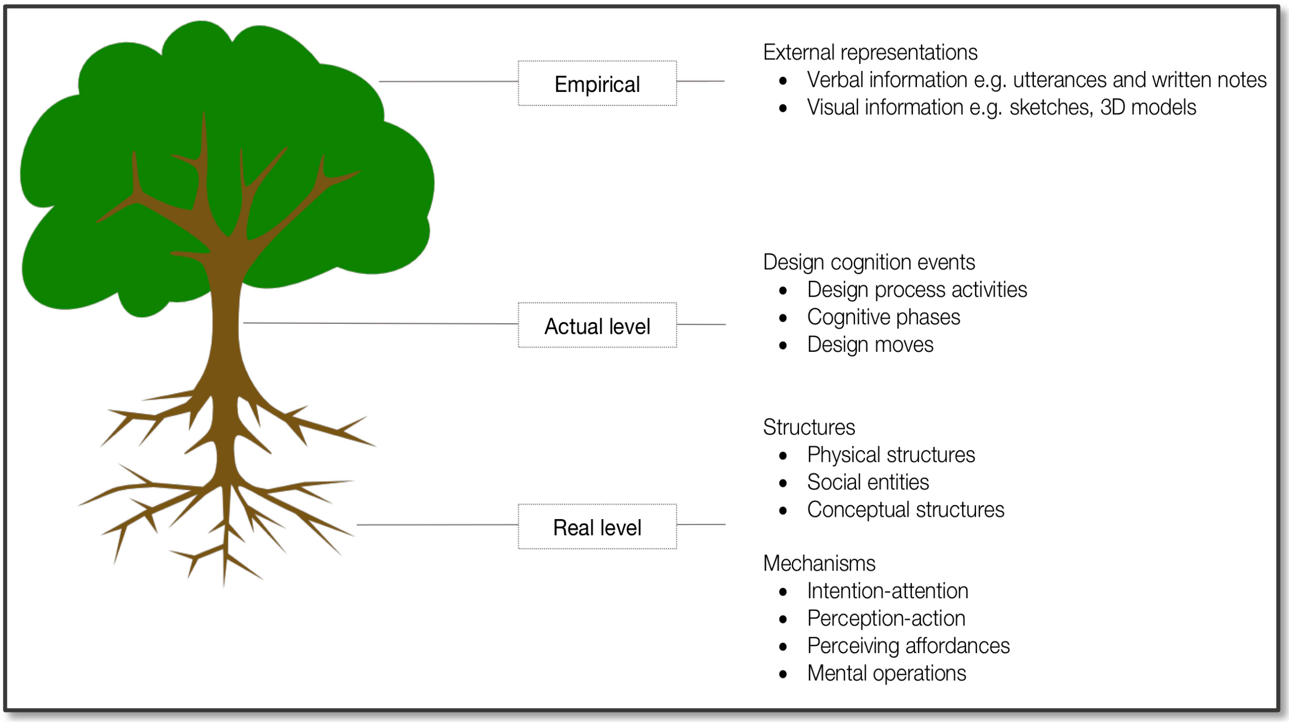


Figure 3.1: Application of Bhaskar's (1975) ontological levels of reality

As captured in Figure 3.1, I had direct access to the participants' external representations at the empirical level, which included verbal and visual information. Having access to the participants' external representations, which were video-recorded, allowed me to further examine the participants' cognitive events that occurred on the actual level. This meant that by studying the external representations of the participants on the empirical level, I could infer the cognitive events during which they were instantiated. The cognitive events that my study focused on included the participants' design process activities (i.e. analysing the problem, formulating constraints and requirements, generating ideas, developing ideas and evaluating ideas) and their cognitive phases (i.e. problem structuring and problem solving).

Furthermore, I examined how each group of participants' collective design process developed by systematically identifying the microscopic design moves (Goldschmidt, 2014). By microscopically analysing the participants' external representations on the empirical level, in relation to their microscopic design moves, I was able to retroductively identify the social, cognitive and physical structures and mechanisms on the real level. I was specifically interested in revealing how the participants' interactions with conceptual, physical and social structures caused them to engage in problem structuring and problem solving.

The final ontological assumption of critical realism relates to reality being viewed from an open system perspective, which cannot be directly controlled by human beings. The complex nature of reality implies that the events generated by structures and mechanisms can never be fully predicted since other mechanisms which may also have causal influences can affect the emergent cognitive events. This implied that I could not make generalisations or predictions of cognitive events based on my investigation of the cognitive mechanisms influencing the participants' design choices. However, instead of trying to predict the generated cognitive events, I focused on explaining how the interaction between mechanisms and structures contributed to emerging cognitive events by studying the participants' verbal and visual external representations. In Table 3.1, I summarise the key ontological concepts that are fundamental for understanding the open systems perspective.

Table 3.1: Summary and relevance of key ontological concepts for the current study

Ontological concepts	Relevance for the study
Structures	A "set of internally related objects or practices" (Sayer, 1992, p. 92) that constitute entities that are objects of knowledge or under study (Danermark et al., 2002), and can be material, social or conceptual in nature. Structures may contain component structures, and may themselves form part of a larger structure (Easton, 2010). In this study, I was interested in participants' interactions with social, conceptual and physical structures within the STEM task environment in order to understand how learners' design problem solving events emerged.
Mechanisms	Causal structures that trigger events, or 'ways of acting of things' (Bhaskar, 1975). Mechanisms exist in the level of the real, and thus exist whether they are enacted or not. For example, cognitive agents have cognitive capacities, but these cognitive capacities are not always instantiated (Menary, 2007). In this study, I was interested in the nature of the mechanisms that facilitated the interaction between social, conceptual and physical structures.
Events	The cognitive events that will result as a consequence of the activation of one or more mechanisms or structures. In critical realism, events are ontologically distinct from the mechanisms that generate them (Danermark et al., 2002). In this study, I examined the participants' design moves as the primary events of interest. In order to gain a better understanding of these, I also examined the cognitive phases and design process activities in which the design moves unfolded. I was able to uncover the design moves, cognitive phases and design process activities by examining the participants' verbal and visual external representations.
Experiences	Events and empirical data that are directly observed and measured by the researcher through their sensory perceptions (Danermark et al., 2002; Wynn & Williams, 2012). Some events may not be directly perceptible, and must be interpreted through the use of theory or indirectly discerned through observation of subsequent perceptible events generated by them (Bhaskar, 1975; Danermark et al., 2002). For this study, my own experiences of the empirical data were largely supported by well-established theoretical frameworks through which I could experience the structures, mechanisms and events involved in the participants' design problem solving.

3.2.2 Epistemological assumptions of critical realism

Five epistemological assumptions underpin critical realism, namely mediated knowledge, explanation rather than that of prediction, explanation *via* mechanisms, the unobservability of mechanisms, and multiple possible explanations (Bhaskar, 1998; Easton, 2009; Wynn & Williams, 2012). In terms of mediated knowledge, critical realism posits that knowledge can exist in one of two domains, being the intransitive and transitive domains. The intransitive domain contains observable phenomena which researchers may seek to explain, while the transitive domain entails the theoretical and conceptual frameworks through which researchers may try to explain observed phenomena (Bhaskar, 1998; Bygstad et al., 2016; Wynn & Williams, 2012).

In this study, the intransitive domain implied the empirical data consisting of the participants' verbal and visual external representations made during the STEM tasks, while my knowledge of the intransitive dimension of the cognitive mechanisms underlying the learners' design problem solving events was formed in the transitive dimension, mediated by conceptual theories found in Extended Design Cognition (Haupt, 2015) and Activity Systems Theory (Engeström, 2015). This implies that my experiences of observable and unobservable cognitive events, structures and cognitive mechanisms were not formed *ex nihilo*, but based on my understanding of existing theoretical frameworks.

Next, the assumption of explanation rather than prediction indicates that critical realism avoids the common positivist goal of predicting that events will occur every time a given set of precedent structures and mechanisms are present (Bhaskar, 1998; Easton, 2009; Wynn & Williams, 2012). Furthermore, because critical realism assumes that reality exists independent of a researcher, critical realist studies do not give first priority to understanding the subjective meanings of events from the researcher's point of view. Critical realist studies rather seek to explain what happened in a particular research context by describing the causal mechanisms that led to certain events. As such, an adequate explanation in critical realism may be sufficient to describe the causal mechanisms linked to the events under investigation (Tsoukas, 1989).

For this reason, I predominantly relied on information processing theories embedded in extended design cognition (Haupt, 2015; Menary, 2010) in my attempt to follow the moment-to-moment sequence of the design moves of the participants during the protocols. By systematically and microscopically tracing the sequences of the design moves of the participants, I was able to identify potential interacting social, conceptual and physical structures that led to the design problem solving of the participants. In addition, macroscopic and microscopic video-recordings allowed me to study the research context in which each cognitive event and triggered mechanism was embedded.

The third epistemological assumption, explanation *via* mechanisms, relates to mechanisms being a suitable strategy for describing phenomena, especially those involving causal relationships (Avgerou, 2013; Bechtel, 2008; Hedström & Ylikoski, 2010). Critical realist research generally aims to explain events or sets of events by describing a mechanism or set of mechanisms that may explain the events. In this study, I aimed to explain the participants' design problem solving in terms of their generated design moves, the design process activities that they executed, and their associated cognitive phases (events) by describing how the participants interacted with their conceptual, social and physical environments (structures).

The assumption of the unobservability of mechanisms implies that some mechanisms may not be perceptible or measurable through human senses or available instrumentation (Bhaskar, 1998; Easton, 2009; Wynn & Williams, 2012). This means that their existence may have to be inferred from effects rather than through direct observation or measurement (Bhaskar, 1975; Easton, 2010). The Extended Design Cognition Theory (Haupt, 2015) and Activity Systems Theory (Engeström, 2015) provided me with a lens through which I could infer the causal mechanisms underlying the participants' design problem solving events in my study.

The final epistemological assumption relates to multiple possible explanations for cognitive events (Bhaskar, 1998; Easton, 2009; Wynn & Williams, 2012). Due to the internal nature of cognitive processing, causal mechanisms are often not directly observable, implying the possibility of more than one possible explanatory mechanism that could be responsible for causing a cognitive event. In such a case, critical realist researchers can employ judgment rationality, i.e. comparing different possible explanations and selecting the one with the greatest explanatory power (Bhaskar, 1998; Easton, 2009; Wynn & Williams, 2012). In an open system ontology, it is possible for more than one cognitive mechanism to lead to the same outcome. In the same way, it is also possible for the same cognitive mechanism to lead to different cognitive events.

3.2.3 Methodological assumptions of critical realism

Wynn and Williams (2012) identify four methodological principles for conducting critical realist research, which are based on the ontological and epistemological assumptions discussed in the previous sections. These principles relate to the explication of events, explication of structure and content, retroduction, and triangulation. For the explication of events, Wynn and Williams (2012) emphasise that critical realist analyses will commence with a comprehensive description of the events, structures and possible mechanisms that led to the phenomenon under investigation. This step requires the inclusion of thick descriptions of the events, sequence of actions, combination of actions and reframing through the lens of existing theory. I documented temporal data while transcribing the verbal data collected in the protocols and written notes of the participants. In addition, I captured all of the external visual representations and gestures that the participants made during the protocols by means of audio-visual recordings and photographs. By capturing the temporal data of each utterance and external representation, I was able to explicate the sequence of actions that unfolded during the participants' STEM tasks. As such, I was able to explicate the moment-to-moment syntactical structure of the learners' thought processes. I chose to analyse the protocols in terms of design moves (Goldschmidt, 2014), which revealed how the participants' design processes incrementally unfolded. I also used a linkograph (Goldschmidt, 2014) to visually represent the syntactical structure of each group of participants' thought processes.

The second methodological principle of critical realism entails the explication of structure and context, which typically occurs once the cognitive events of the STEM tasks have been captured in terms of design moves. During this process, researchers will typically attempt to identify the structures and mechanisms that are causally relevant to the phenomena or events under investigation (Bygstad et al., 2016; Wynn & Williams, 2012). In this study, this meant that I had to analyse the semantic structure of the participants' thoughts as evident in their verbal and visual representations. By explicating the incremental moment-to-moment development of learners' thought processes, I was able to start plotting the structures and mechanisms that might have caused the participants' design problem solving events. In order to determine the structures and mechanisms that were causally related to their design problem solving events, it was furthermore necessary to understand the context in which the participants' external representations were instantiated. This resulted in me thoroughly viewing the video-recordings in order to compile thick descriptions of the participants' design moves by coding their interactions in the physical and social environments. As during the other processes involved in this study, these interactions were governed by my understanding of Extended Design Cognition (Haupt, 2015) and Activity Systems Theory (Engeström, 2015).

As the central goal of a critical realist study is to describe the causal mechanisms and their relation to the structures that led to the events under study, Wynn and Williams (2012) explain that critical realists need to adopt retroductive logic during data analysis. In understanding the methodological principle of retroduction, one can be guided by the origins of the concept. The prefix '*retro*' in Latin means to deliberately go backward. In addition, the combination of '*retro*' with the suffix 'ductive*'* from the Latin '*ducere'*, means to lead, thereby emphasising retroductive logic as a process of deliberately leading backward. In this study, this implied that when I identified the participants' cognitive events, I iteratively went backward and forward to examine the structures and mechanisms that led to the instantiation of cognitive events. In this manner, retroductive logic allowed me to propose the existence of structures and mechanisms that explained how the observed design problem solving events, within their specific contextual conditions, were instantiated.

Finally, the methodological principle of triangulation in critical realist research relates to the view that the social world is made up of a variety of types of structures, including conceptual, social, cognitive and physical structures. These entities entail a variety of causal capacities operating at a number of individual, group and societal levels. Some of these structures and mechanisms are, however, inherently unobservable due to their internal nature and cannot be empirically experienced except through their effects in the external environment. Therefore, in order to understand the causal capacities formed by these structures, it is useful to collect a variety of data types (Bygstad et al., 2016; O'Mahoney & Vincent, 2014; Wynn & Williams, 2012). In this study, triangulation was beneficial as some of the structures and their causal capacities were difficult to understand using only one data source. For example, the manner in which the participants perceived useful information from the external environment could not be sufficiently captured in their verbal utterances, but was easily captured by video-recordings, which I could rely on to observe what the participants looked at or pointed towards during the completion of the STEM tasks.

3.2.4 Axiological assumptions of critical realism

In critical realism, axiological assumptions refer to the role that values play in the research process (Creswell & Plano Clark, 2018). The axiological implications of taking a critical realist stance in this research relates to my research being value-laden and theory-laden, thereby being partly biased (Danermark et al., 2002). While I acknowledge the fact that I used a range of theoretical frameworks to identify the structures and causal mechanisms underlying the participants' design choices, my interpretations of the data cannot be removed from my own subjective view of cognition in general. This may be ascribed to my experiences as a researcher and academic, as well as the fact that my own background differs from that of the participants. During my analysis and interpretation of the results, I aimed to maintain a neutral writing style by comparing different theoretical lenses to the collected data in an attempt to write with critical objectivity. In addition, I relied on reflexivity to avoid subjective and biased interpretations as far as possible (Creswell & Plano Clark, 2018).

3.2.5 Rationale for adopting a critical realist stance

I selected critical realism as my epistemological paradigm due to the retroductive reasoning approach to causality that is embedded in critical realism, and the purpose of my study relating to exploring, describing and explaining the cognitive mechanisms of learners' design cognition. This paradigm enabled me to iteratively study the ways in which the participants' design problem solving events emerged as a result of their interactions with social, conceptual and physical structures in their learning environments while completing their STEM tasks. As such, I was able to exhibit how mechanisms, including perception-action and intention-attention bridged the internal worlds of the participants and their external environments in order to facilitate emerging design problem solving events. Essentially, the retroductive approach underlying critical realism allowed me to infer complex interrelationships between the internal worlds of the participants and their environments by backwardly studying the sequence in which their design moves and external representations were made in order to identify the causal structures and mechanisms that had an effect on their design problem solving events.

Another reason for my decision to study the participants' thinking processes from a critical realist perspective is based on Bhaskar's (1975) levels of ontology. The implication of this layered view of ontology is that mental structures and mechanisms are treated as equal to physical 'real' ones and hold equal potential for influencing learners' design problem solving events. From an Extended Design Cognition viewpoint (Haupt, 2015), this was essential since I avoided approaching the participants' cognitive processes exclusively from an internalist or radical externalist conception of cognition.

Finally, critical realism allowed me to conceptually decompose the cognitive system of each case into its core ontological concepts, which are captured in Figure 3.2. By decomposing the cognitive system of each case into component events, structures and mechanisms, I was able to identify discreet cognitive events that I could code, analyse and interpret (Cash et al., 2015). The cognitive events referred to object-oriented activities (Engeström, 2015) and were defined by the design process activity and the design intention of the participants' conversations. The situational context in which each event could be decomposed was defined by the participants' interactions with social, conceptual and physical structures and the mechanisms that were triggered during each interaction.

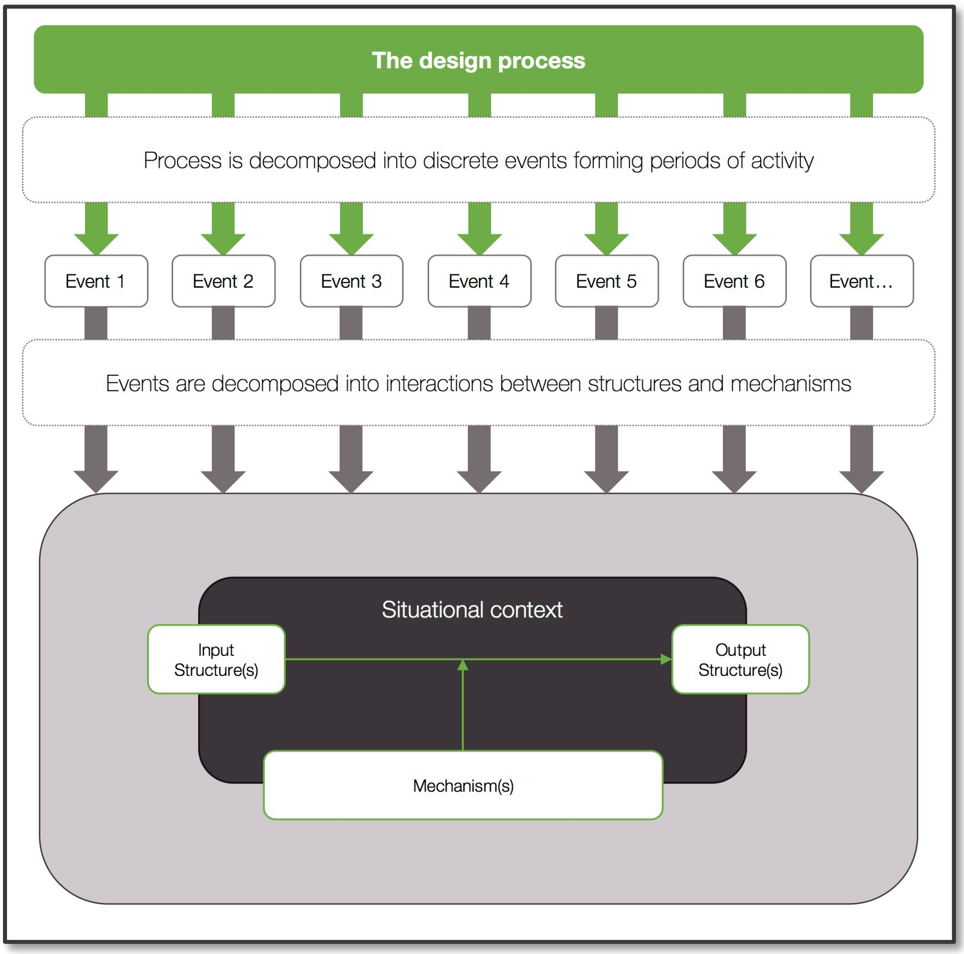


Figure 3.2: A critical realist perspective on the design process (adapted from Cash et al., 2015)

Even though some scholars have critiqued the critical realist paradigm on the basis of some of its principles being similar to pre-existing research paradigms, Mingers (2004, p. 147) states that critical realism "does not [...] just dismiss competing philosophies but tries to incorporate within itself that which is valuable". As such, a critical realist paradigm does not claim the novelty and uniqueness of its positions, but rather advocates for the explanatory power of its ontological and epistemological assumptions – which is not supported by other paradigms.

3.3 RESEARCH APPROACH

Researching the way in which the participants engaged in design problem solving events through the lens of critical realism required multiple and diverse tools. To this end, I followed a QUAL + quan mixed methods approach in conducting this study. I selected this parallel mixed methods approach (Teddlie & Tashakkori, 2009) based on my belief that such an approach would allow me to simultaneously study a range of data sources by means of an *a priori* coding scheme while searching for emergent quantitative trends and qualitative themes.

Tashakkori and Teddlie (2012) propose nine defining characteristics of mixed methods studies. These characteristics provided me with a useful guide in undertaking this research, as explained in Table 3.2 in terms of the salient features of this study.

Table 3.2: Reflection on the salient features of my study in relation to Tashakkori and Teddlie's (2012) characterisatics of mixed methods research

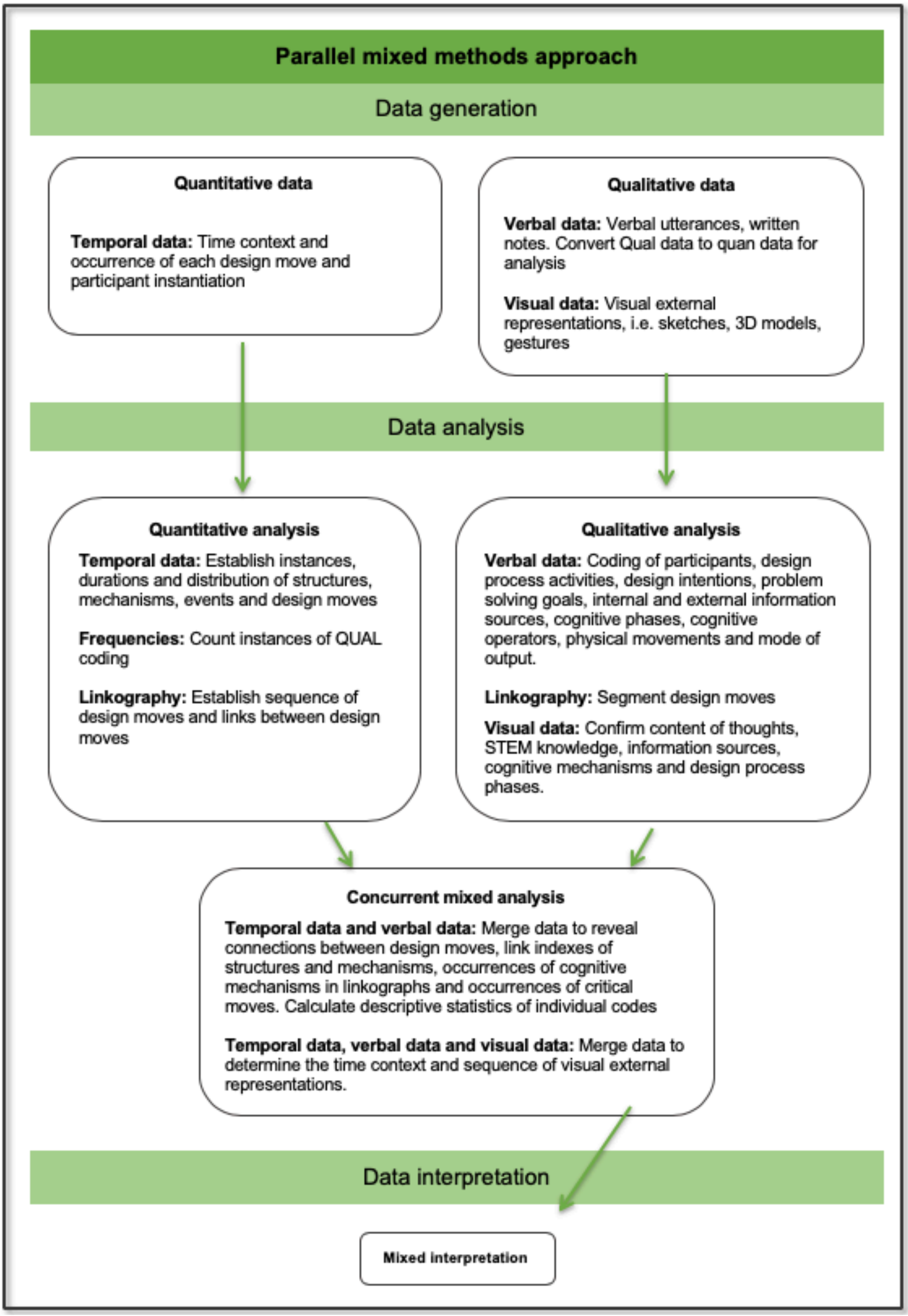
Characteristic	Application in the current study
Methodological eclecticism	I integrated multiple data generation methods. QUAL data derived from the verbal protocols formed my primary data source. Verbal data were mapped by means of written notes, temporal instances, sketches, and 3D modelling activities. I qualitatively analysed and interpreted the data, supported by quantitative counts, sequences and distributions.
Paradigm pluralism	Although I considered other possible paradigms available as the underlying philosophy for this study, critical realism seemed to be the most appropriate paradigm, thereby incorporating benefits from a variety of choices. Furthermore, critical realism developed as a result of the limitations of other paradigms. It integrates ontological, epistemological, methodological and axiological assumptions from various paradigms based on the focus and purpose of my research.
Emphasis on diversity at all levels of the research enterprise	Firstly, I incorporated a diverse range of theoretical lenses, including the Extended Design Cognition (Haupt, 2015) and Activity Systems Theories (Engeström, 2015) through which I could interpret my data to reveal structures, mechanisms, and cognitive events on multiple ontological levels of reality. I also utilised a diverse range of data types, including verbal data and visual data. The data sources comprised the verbal utterances, written notes, 3D models and sketches of the participants. In addition, I quantified the qualitative coding to produce quantitative data, in the form of frequencies, sequences, and distributions. By emphasising the diversity of theoretical frames and data collection methods and analyses, I emphasised diversity during all phases of the research process.
Emphasis on integration rather than dichotomies	I considered a range of theoretical frameworks that could be integrated to explain different levels of reality. I did not separate or dichotomise my explanations of reality in any manner. Furthermore, by transforming qualitative data into quantitative data, I emphasised the integration of data in order to provide rich, meaningful findings, which only one data type would not necessarily have provided.

Iterative cyclical approach to research	My research cycle moved from empirical observations of cognitive events through studying the external representations of the participants, to identifying the structures and mechanisms underlying the participants' design cognition. This investigation allowed me to move backwards and forwards to identify these structures and mechanisms. Studying my own coding of structures, mechanisms and events allowed me to generate temporal instances, counts and distributions through which I could inductively make general inferences about the participants' interactions with social, cognitive and physical structures. From these general inferences about the participants' interactions, I moved through deductive logic to tentative hypotheses about the mechanical role of social, cognitive and physical structures in the behaviour of the participants.
Focus on research questions in determining methods employed	My research questions were central to choosing a research paradigm. Choosing critical realism as paradigm then presupposed congruence between the ontological, epistemological, methodological and axiological assumptions relevant to this study. These assumptions furthermore determined how I generated, documented, analysed and interpreted the data, and enhanced the quality and dissemination of my research findings.
'Signature' research designs and analytical processes commonly agreed upon	I followed a parallel mixed methods research approach that is commonly agreed upon as one of the signature mixed methods research designs. This means that I concurrently generated, documented, analysed and interpreted QUAL + quan data.
Implicit tendency towards balance and compromise	I attempted to provide a balanced view between QUAL + quan data. I specifically attempted to provide a complementary and dialectic marriage between the two approaches.
Reliance on visual representations	My data analysis required the use of visual representations in order to simplify the complex relationships between QUAL + quan elements. To this end, I used visual representations such as diagrams, tables, graphs and linkographs to illustrate the relations between findings from the QUAL + quan data.

By combining qualitative and quantitative data generation, documentation and analysis methods, I attempted not only to provide rich descriptions of the participants' design problem solving events, but also to enhance the trustworthiness of this study through data triangulation. As such, I subscribed to Denzin's (1970) notion of methodological triangulation. In accordance with the critical realist methodological principles that I upheld, the use of methodological triangulation in this study implied that I used more than one method for data generation, documentation and analysis respectively.

As not all structures and mechanisms are observable, and can only be identified in terms of their effect on the environment, it was important for me to generate as many data sources as possible that might provide sufficient evidence to adequately address my research questions. Collecting data in multiple ways at the same time allowed me to generate rich descriptions of the participants' thinking processes during their STEM tasks. As such, a parallel mixed methods approach seemed appropriate as I could generate multiple data sources and engage in deep levels of analysis by mixing quantitative and qualitative analysis methods, which a single approach would not necessarily have allowed me to do (Creswell, 2014).

Figure 3.3 provides an overview of the parallel mixed methods research approach that I followed during this study. I discuss my selected approach in the remainder of the section.



Quantitative data

Temporal data: Time context and occurrence of each design move and participant instantiation

Qualitative data

Verbal data: Verbal utterances, written notes. Convert Qual data to quan data for analysis

Visual data: Visual external representations, i.e. sketches, 3D models, gestures

Quantitative analysis

Temporal data: Establish instances, durations and distribution of structures, mechanisms, events and design moves

Frequencies: Count instances of QUAL coding

Linkography: Establish sequence of design moves and links between design moves

Qualitative analysis

Verbal data: Coding of participants, design process activities, design intentions, problem solving goals, internal and external information sources, cognitive phases, cognitive operators, physical movements and mode of output.

Linkography: Segment design moves

Visual data: Confirm content of thoughts, STEM knowledge, information sources, cognitive mechanisms and design process phases.

Concurrent mixed analysis

Temporal data and verbal data: Merge data to reveal connections between design moves, link indexes of structures and mechanisms, occurrences of cognitive mechanisms in linkographs and occurrences of critical moves. Calculate descriptive statistics of individual codes

Temporal data, verbal data and visual data: Merge data to determine the time context and sequence of visual external representations.

Figure 3.3: Parallel mixed methods approach

I simultaneously analysed and interpreted the quantitative and qualitative data (Tashakkori & Teddlie, 2003). I namely analysed the verbal utterances of the participants qualitatively by coding the participants' design process activities, design intentions, problem solving goals, internal and external information sources, cognitive phases, cognitive operators, physical movements and mode of output as expressed by the participants. My final inferences were accordingly based on both QUAL + quan data analysis results.

3.4 RESEARCH DESIGN

I implemented a multiple case study research design (Stake, 2006; Yin, 2018), which guided my decisions regarding the generation, documentation and analysis of data, thereby allowing me to address my research questions and produce trustworthy findings. In this study, I regarded a case as "an integrated system" with specified boundaries and "working parts" (Stake, 1995, p. 2). This understanding of a case allowed me to view each group of participants that were selected for this study as an integrated cognitive system that could be studied within the boundaries of their physical technology classroom. Creswell (2014) furthermore describes case study research as research where researchers investigate a single case or multiple cases over time, through detailed, in-depth data generation generally relying on a range of data sources. As such, I investigated three different cases involving multiple data generation, documentation and analysis strategies.

For this study, I concur with Patton (2015), who regards the process of boundary setting as essential in determining the particular case and focus of an inquiry. I regarded a case study design as suitable for this study as I was interested in studying how a specific group of participants engaged in a specific STEM task in the context of Grade 8 technology classrooms (Yin, 2018). I specifically investigated how the participants' design problem solving events emerged by studying each group of participants as an integrated cognitive system. This implied that I could analyse each group of participants in terms of their internal and external constituents through the lens of Extended Design Cognition Theory (Haupt, 2015) and Activity Systems Theory (Engeström, 2015). In alignment with the critical realist stance that I selected, I acted as an observer and an interpreter; and attempted to identify the transitive and intransitive structures, events and experiences that led to the emergence of the participants' design problem solving events.

As stated, I implemented a multiple case study design (Stake, 2006; Yin, 2018) as I selected three different school settings as cases in which I could study how learners engaged in design problem solving. In my view, these cases represent a heterogeneous sample of technology learners engaged in STEM tasks in medium-resourced school settings (Creswell, 2014). I articulate the focus as well as the boundaries of the selected cases in Figure 3.4.

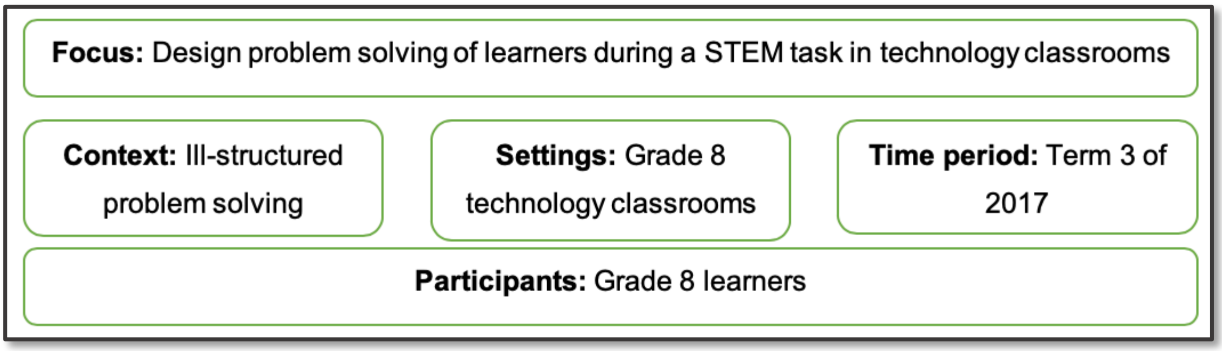


Figure 3.4: Focus and boundaries of the selected cases (adapted from Patton, 2015)

In conducting case study research, I faced the limitation of the generalisability of the findings. However, case studies conducted within a critical realist paradigm are not aimed at generalising findings from samples to populations, but rather focus on gaining in-depth understanding of specific cases. In this study, this was the case in terms of discovering causal mechanisms that are hypothesised to have generated observed cognitive events (Easton, 2009; Wynn & Williams, 2012). It follows that critical realist studies are concerned with theoretical generalisations (Wynn & Williams, 2012) rather than the generalisation of findings. In this regard, Stake (1995) argues that the true emphasis of case study research is "particularization, not generalization" (1995, p. 8), which implies that an understanding of each case forms the core of the research. In addressing this potential limitation of case study research, I followed Creswell's (2014) suggestion to provide a thick description of each case, followed by a description of the underlying themes emerging across the investigated cases. As such, I aimed to gain a deep understanding of the cognitive mechanisms underlying the participants' design problem solving events. Despite generalisability not being likely, certain tendencies may be transferable to similar contexts in other South African classrooms as other classrooms might display similar characteristics to the cases described in detail in this thesis (Stake, 1995). Furthermore, I anticipate that the insight generated from the three selected cases may contribute to an understanding of some of the potential structures and mechanisms underlying learners' design problem solving events during the STEM tasks that they completed.

Wynn and Williams (2012) assert that during case selection, critical realist studies are concerned with identifying a unique set of structures that can allow for an investigation of the cognitive events under study. This means that critical realist case studies often involve a single case, or a limited set of cases, thereby allowing critical realist researchers to obtain detailed, context sensitive explanations of the cognitive mechanisms they are studying (Wynn & Williams, 2012). For the sake of theory, Wynn and Williams (2012) suggest that critical realist researchers utilise existing theories as the means to analyse the data that they obtain. In this manner, cognitive events in cases can be abstracted and the cognitive mechanisms under investigation observed in action through the lens of the selected transitive theories. I accordingly applied this approach in my study using an Extended Design Cognition framework (Haupt, 2015) in conjunction with Activity Systems Theory (Engeström, 2015) to assist me in the structural analysis of each case.

3.5 RESEARCH PROCESS

Having framed my research paradigm and research approach, I was able to plan and conduct my study against the background of the selected research design. Figure 3.5 captures the stages of the research process that I executed in order to address the research questions, as presented in Chapter 1. My discussion of the various selection procedures and data generation, documentation, analysis and interpretation strategies follow in the subsequent sections.

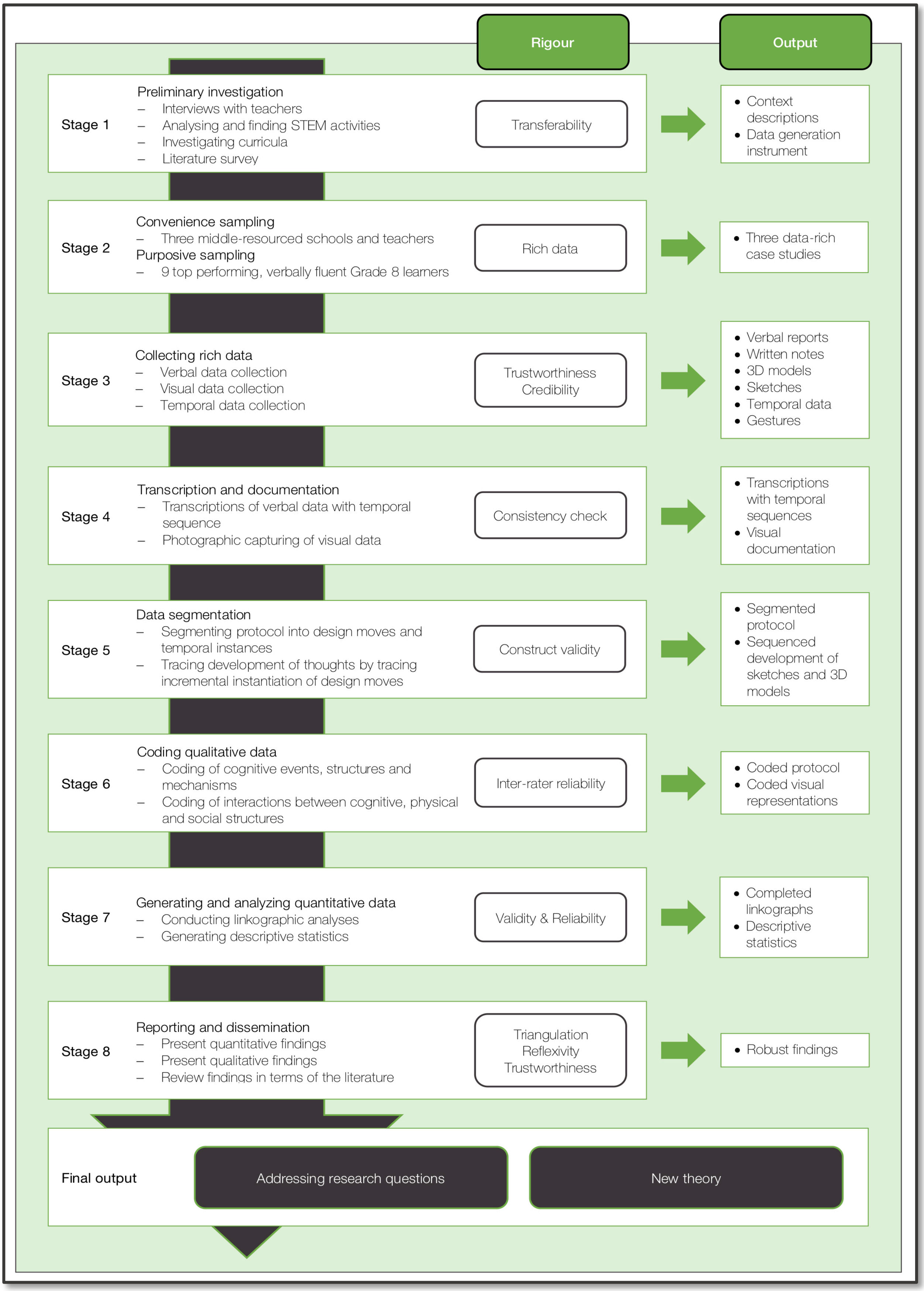


Figure 3.5: Stages of the research process

3.5.1 Selection of cases and participants

In this study, I relied on a combination of non-probability sampling techniques to select three research sites in which groups of learners could each complete an integrated STEM task. For this purpose, I combined convenience and purposive sampling strategies. Convenience sampling entails the process of selecting participants based on geographical proximity, availability of the setting and participants, accessibility, and the willingness of the participants to participate (Maree & Pietersen, 2007). Some authors criticise convenience sampling as being “lazy and largely useless” (Patton, 2015, p. 309) with the possible danger of resulting in information-poor data and findings with poor credibility.

I do not regard this limitation as applicable to this study as I combined convenience sampling with purposive sampling. I relied on convenience sampling to select the three participating schools based on their geographical proximity (Tshwane South and Tshwane West) and their availability for research during the third term of the school calendar (July to September 2017). To sample the selected cases, I obtained a list of all public schools that are situated in Tshwane South, Tshwane West and Tshwane North as these districts are within easy reach from my place of work, and therefore easily accessible. I then relied on convenience sampling to gain access to three schools through student teachers who were in their final year of study at the University of Pretoria when I commenced with my study. The student teachers, whom I regard as gatekeepers, brought me into contact with senior technology teachers at the respective schools.

Although the three sampled cases were conveniently available, my central concern was to generate rich data that would provide sufficient evidence of the social, conceptual and physical structures and mechanisms that may affected learners’ design problem solving events for me to be able to address my research questions (Yin, 2018). For this reason, I requested the three senior technology teachers to each purposively select six participants in their respective classes (two groups of three learners each). In order to purposively select the six participants per school, I provided the teachers with the following selection criteria:

- The participants had to be Grade 8 learners in one of the selected schools.
- The participants had to be top performers in Science, Mathematics and Technology subjects.
- The participants had to be able to work together effectively with other participants in the group.
- The participants had to be able to communicate effectively with verbal and visual representations, either in English or Afrikaans, which are the two languages that I am fluent in.
- The participants had to be available for data generation sessions after school hours and they and their parents had to provide informed consent (parents) or assent (learners).

I provide an overview of the cases and participants that I selected in Table 3.3.

Table 3.3: Overview of the cases and participants

Cases	**Case 1**	**Case 2**	**Case 3**
Description	A medium-resourced school, accessed *via* a student-teacher during teaching practice from the University of Pretoria	A medium-resourced school, accessed *via* a student-teacher during teaching practice from the University of Pretoria	A medium-resourced, school, accessed *via* a student teacher during teaching practice from the University of Pretoria
Type of sampling	Convenient sampling	Convenient sampling	Convenient sampling
Criteria for selection	Conveniently located within Tshwane South	Conveniently located within Tshwane West	Conveniently located within Tshwane South
Participants	**n = 6**	**n = 6**	**n = 6**
Group 1 composition	1 female 2 males	2 females 1 male	0 females 3 males
Group 2 composition	0 females 3 males	2 females 1 male	0 females 3 males
Type of sampling	Purposive sampling	Purposive sampling	Purposive sampling

In cautioning against the use of proximity and convenience when selecting the research setting and participants, I thus aimed to obtain data that would enable me to address my research questions. For this purpose, I applied another round of purposive sampling once data generation had been completed in order to select one of the two groups of participants per school based on the criterion of analysing the three cases with the highest level of richness of data. Furthermore, as I was not influenced by the amount and quality of the data that were generated by the participants, the selected cases were of secondary importance, with my primary aim being that of gaining insight into the ways in which the participants' design problem solving events emerged as a result of their interactions with social, conceptual and physical structures (Stake, 2000; Yin, 2018).

I regard the way in which I selected the cases and participants as appropriate for this study for a few reasons. Firstly, by sampling learners who had been recognised for their academic achievement in science, mathematics and technology education, I assumed that the participants would possess the necessary internal structures and mechanisms to adequately engage in the given STEM task, having mastered the taught conceptual and procedural knowledge in these subjects. Secondly, I attempted to ensure rich data generation by sampling groups of learners who were fluent in their interactions and could effectively cooperate with members of the group, providing rich utterances. From my previous experience in design cognition studies I realised that group members who are unfamiliar with each other will often struggle to engage in joint action. As such, I requested teachers to select groups of participants who had effectively worked together on previous science, mathematics or technology projects.

Thirdly, I asked the teachers to select learners who they viewed as verbally and visually able to communicate their design ideas in order for me to obtain rich data, as verbal utterances provided me with access to the internal worlds of the participants from which I could infer structures and mechanisms during designing events. I also requested that learners would also be able to visually communicate their thoughts in order to be able to generate rich data. In the following sections, I provide some background on each of the three research sites (schools) and cases (groups of participants) that formed part of my study. All three sites shared the characteristic of having medium-resourced science, technology and mathematics classrooms. This implies the availability of a fair amount of teaching and learning support materials in the science, technology and mathematics learning environments.

Within the South African public school setting, medium-resourced classrooms will typically depend on teaching and learning resources received from the Department of Basic Education, yet will also source additional resources, tools and materials for learners to use. All medium-resourced classrooms can be taken as classrooms that will comply with the minimum resource requirements stipulated in the Technology CAPS (DBE, 2011, p. 13) and Natural Sciences CAPS document (DBE, 2011). In Table 3.4, I include a list of resource requirements for technology and Natural Sciences as stipulated by the South African Department of Basic Education, with which the three selected schools (classes) complied.

Table 3.4: Resource requirements for Technology and Natural Sciences (Department of Basic Education, 2011)

Resource requirement	Compliance by three participating schools
Each learner must have an appropriate textbook.	All three of the participating schools provided their learners with the prescribed science, technology and mathematics textbooks.
Each learner must have a 72-page A4 workbook.	All participants had their own workbook.
Required stationary includes basic drawing instruments: pencil, eraser, ruler and set squares.	The participants had access to basic stationery items and drawing instruments in all three schools.
Designated teaching venues for science, technology and mathematics.	All three schools had different science, mathematics and technology classrooms.
Science, technology and mathematics rooms must be secure, with doors that lock, and with burglar proofing if possible. Enough cupboards should be available to store and lock away all resources	All three science, technology and mathematics classrooms were secured with doors that lock and with burglar proofing. All of the classrooms had enough cupboards and storage space for tools, materials and school projects.
It is the responsibility of the school to provide each learner with the minimum tools and material to meet the needs of the subject.	All three schools provided learners with the minimum tools and materials to conduct scientific experiments and technology projects.

My rationale for selecting medium-resourced schools is based on my view that low-resourced schools would not necessarily comply with the basic resource requirements as stipulated by the Department of Basic Education (2011), neither would such schools be likely to have access to socio-technological resources with which learners can interact in class. On the other hand, my decision to exclude well-resourced schools was based on the tendency of such schools to have access to various state-of-the-art information resources such as extra-ordinary teaching and learning support materials, including robotics, modern educational technologies, classroom technicians, tradesmen and expert technologists within the school community, resulting in the possibility of sourcing their own learning and teaching materials instead of depending on other institutions.

In the following sub-sections, I provide a brief description of each case that I studied. I also refer to what they did during the second school term in the subject technology, and then explain how I designed the STEM task accordingly.

3.5.1.1 Research site and Case A

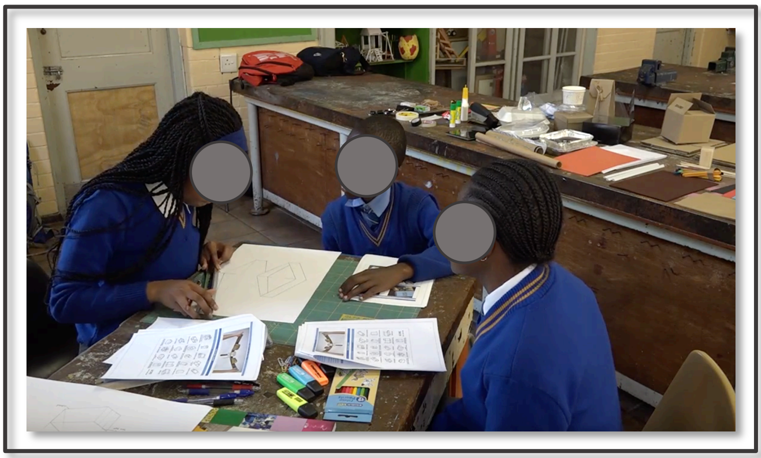
The first research site was a combined, technical school situated in the Tshwane South district. This school caters to a range of learners from low, medium and high socio-economic backgrounds. Photograph 3.1 provides an image of the technology classroom of School A and the three participating learners.

Photograph 3.1: Case A

In the school term prior to this study, the Grade 8 learners in Case A focused on the topic ‘Processing’ in class, as stipulated by the CAPS document (Department of Basic Education, 2011). As a problem context and to guide their work, the teacher had used the theme of pollution to situate all learner activities during the second term. For this purpose, learners investigated various types of pollution and the negative impact of pollution on the environment. Learners then engaged in case studies that focused on (i) The impact of aluminium packaging on the environment, and (ii) The importance of using biodegradable materials. Subsequently, the teacher engaged the learners in a design project derived from Johnstone et al. (2013) where learners had to upcycle aluminium cold drink cans that could be processed for a different purpose than intended in order to counteract the effects of pollution on the environment.

3.5.1.2 Research site and Case B

The second research site was a combined school situated in the Tshwane West district in a low-socio economic area. Although the school is situated in a low-socio economic area, it is still a medium-resourced school, meeting the criteria of the Department of Basic Education (2011). As such, sufficient tools and materials were available in the science and technology classrooms for project purposes. Photograph 3.2 captures the classroom environment in School B as well as the participating Grade 8 learners.

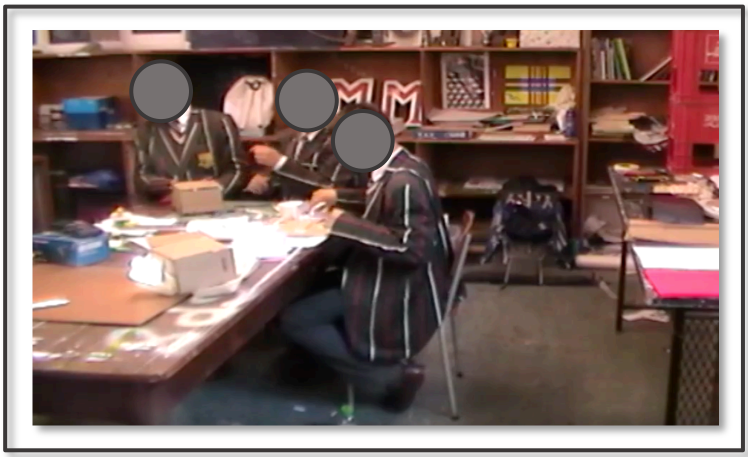


Photograph 3.2: Case B

Prior to this study, the Grade 8 learners in School B also completed a term of work focusing on the topic ‘Processing’ as stipulated by the CAPS document (Department of Basic Education, 2011). The learners from School B investigated different types of plastics in order to ascertain which types of plastics can and cannot be recycled. Learners also investigated the different types of packaging materials, including paper and boards, textiles and plastics, and their properties. The teacher used case studies to emphasise the importance of recycling and using biodegradable materials in the manufacturing of packaging materials. Based on the prescribed content, the teacher used a design task from Moodley, Naidoo and Gayadeen (2013) on which to base the learners’ Practical Assessment Task (design project). For this project, learners were guided to design and make packaging for children’s sandals. Furthermore, the design project required of the learners to make the packaging from transparent and non-transparent materials.

3.5.1.3 Research site and Case C

Research site C is an all-boys school situated in the Tshwane South district. Although this school is situated in a medium to high socio-economic area, it caters to learners from low, medium and high socio-economic backgrounds. Photograph 3.3 shows the technology classroom of School C and the three participating learners.



Photograph 3.3: Case C

The teacher from School C engaged her learners in a variety of case studies for the duration of the second school term. The purpose of these case studies was to make learners aware of the general problem that plastic causes in the environment. Learners were exposed to videos explaining the detrimental effects of plastic, and were also shown some inspirational videos on possible solutions. Learners furthermore investigated a variety of existing biodegradable products to understand some solutions for plastic pollution. This case did not include a design project from a textbook as the teacher did not regard these as suitable. Instead, the teacher decided to design her own project where learners had to design and develop their own 'conceptual' solution to a plastic pollution problem.

Therefore, even though the teachers in all three cases differed in their approaches as to what was taught during the second school term prior to this study, and how it was taught, all three teachers focused on developing an awareness of the negative effects of unrecyclable and non-biodegradable materials on the environment. Furthermore, in all three cases the learners were given opportunities to investigate alternative types of materials that could be used to reduce the negative impact of non-recyclable materials on the environment, or reuse existing items for different purposes. Based on this, I decided to adapt an existing design task that focused on the negative effects of polystyrene on the environment for the purpose of this study.

3.5.2 Pre-data generation phases

Prior to generating the data through a TAPS methodology, I had to complete a few actions in preparation of my involvement with the participants. I first had to gain access to and obtain background information from the three senior technology teachers; secondly, I had to select and finalise an ill-structured STEM design task; and thirdly I had to prepare the classroom environments for the data generation to take place.

3.5.2.1 Gaining access and obtaining background information

Apart from asking permission from the University of Pretoria and the Gauteng Department of Education, I sought permission to conduct research from the three school principals, their School Governing Body's and the respective senior technology teachers. For this purpose, I visited each of the three schools on several occasions and engaged in discussions with the principals and senior technology teachers to explain the nature and purpose of my research, the research process, and what the teachers' and learners' involvement would entail, as well as to obtain informed consent. Refer to Appendix A and B for the letters related to the permission for my study to be conducted, as well as the informed consent/assent I obtained.

After obtaining informed consent from the three senior technology teachers, and before commencing with the data generation, I engaged in three additional meetings with each teacher. During these meetings, I aimed to obtain insight into the culture embedded in each of the three schools and classes. I also enquired about the work that the Grade 8 learners had been doing and which information sources, tools and materials the learners usually worked with during their design projects and general class work.

I specifically needed to understand what the learners had been doing in class in order for me to plan a STEM task that would build on the participants' prior knowledge. During our initial meetings, the senior technology teachers thus showed me their lesson planning for the second school term as I conducted this study in the third term. The teachers also provided me with examples of the learners' project portfolios for me to view what the learners had done and in which sequence they completed their activities. I paid attention to the activities they engaged in, and what was required of them by each of their teachers, using this information to formulate the ‘instructions’ section of the STEM design task that I compiled.

During my second round of meetings with the teachers, I requested them to show me their classrooms. In observing the classrooms, I paid attention to the available tools and materials in each classroom and then used this information to determine which tools and materials I would supply for the STEM task that formed part of my data generation. Apart from my own classroom investigation, I also discussed the selection of suitable participating learners with the teachers on these occasions, specifically in terms of the required selection criteria. The teachers subsequently each compiled a list consisting of six to 12 possible participants for this study based on their knowledge of the learners’ abilities to work together effectively and their abilities to verbally and visually communicate. After compiling these lists of possible participants, the teachers distributed informed consent letters to the parents.

After the participants’ parents agreed to their participation, I met with the teachers and selected learners, requesting them to complete the informed assent letters. I explained the research project to them and what their role as participants would entail. I emphasised that their parents had already given informed consent and also ensured that the learners understood that they could withdraw from the research at any time if they wished to do so, without any negative effect. In concluding these meetings, we arranged suitable dates and times to conduct the TAPS recordings. As I did not video-record these sessions during the participants’ normal tuition hours, we required specifically allocated times that would suit the teachers, learner participants and myself. In Table 3.5, I summarise the detail of the various meetings that I had with the technology teachers as well as the data generation meetings that followed. I include the voice recordings of these meetings in Appendix C3.

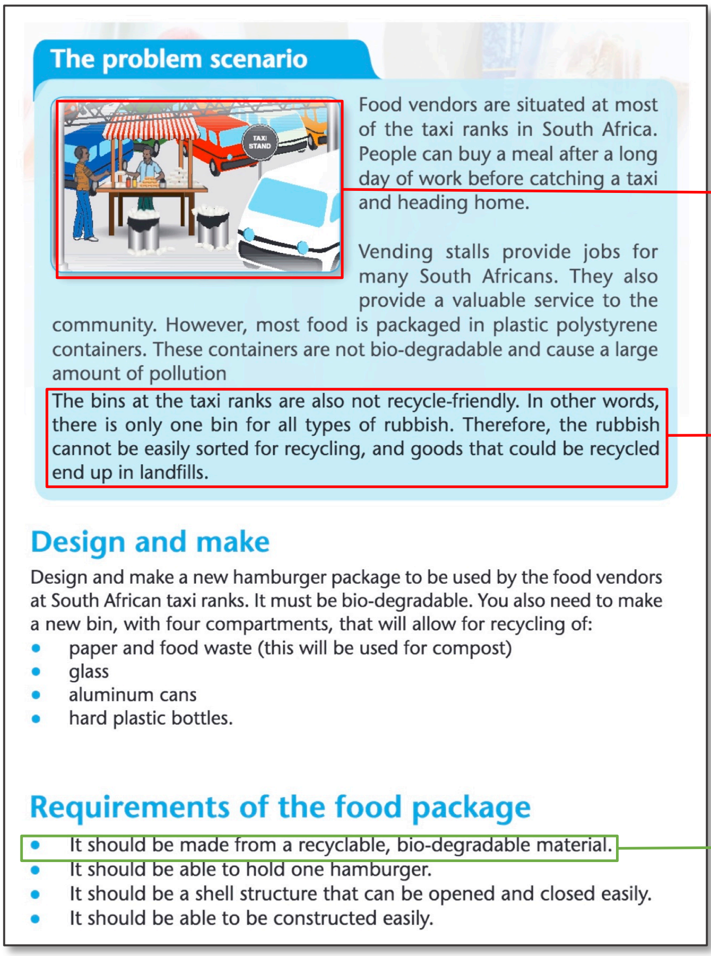
Table 3.5: Summary of the teacher meetings and data generation sessions

Description	Duration	Case A	Case B	Case C
Gaining information about the previous term’s work and viewing lesson plans	2 hours	17 May 2017	24 May 2017	22 May 2017
Inspection and investigation of the classrooms and sampling	1 hour	23 May 2017	29 July 2017	18 August 2017
Informed assent session with the learner participants and discussion of the layout of the TAPS environment	2 hours	1 June 2017	3 August 2017	21 August 2017
Data generation dates	4 hours	11-12 June 2017	10-11 August 2017	28-29 August 2017

3.5.2.2 Selecting and finalising the STEM design task

In order to design a data generation instrument that could enable me to gain insight into the design behaviour I set out to study, I adapted a task from a textbook titled “Technology for all” (Bosch et al., 2013), which is prescribed by the South African Department of Basic Education for Grade 8 learners in technology. The existing design task is captured in Figure 3.6 on the left side of the text box.

Original design task (Bosch et al., 2013), **Adapting the design task**



The problem scenario

Food vendors are situated at most of the taxi ranks in South Africa. People can buy a meal after a long day of work before catching a taxi and heading home.

Vending stalls provide jobs for many South Africans. They also provide a valuable service to the community. However, most food is packaged in plastic polystyrene containers. These containers are not bio-degradable and cause a large amount of pollution

The bins at the taxi ranks are also not recycle-friendly. In other words, there is only one bin for all types of rubbish. Therefore, the rubbish cannot be easily sorted for recycling, and goods that could be recycled end up in landfills.

Design and make

Design and make a new hamburger package to be used by the food vendors at South African taxi ranks. It must be bio-degradable. You also need to make a new bin, with four compartments, that will allow for recycling of:

- paper and food waste (this will be used for compost)
- glass
- aluminum cans
- hard plastic bottles.

Requirements of the food package

- It should be made from a recyclable, bio-degradable material.
- It should be able to hold one hamburger.
- It should be a shell structure that can be opened and closed easily.
- It should be able to be constructed easily.

Only one picture was provided in the whole design task regarding the problem context. For my design task, I kept the problem context, but added more contextual information in the form of pictures.

The second design problem was unnecessary for the purpose of this study. I only focused on designing suitable packaging.

I kept the main requirement to design a recyclable, biodegradable food packaging container – but changed the food from a hamburger to pap, meat and gravy to justify my reason for adding heat transfer as a scientific concept to be considered during designing.

Figure 3.6: Adapting the existing design task taken from (Bosch et al., 2013, p. 123)

Although none of the participating schools had used this textbook for their Grade 8 curriculum, my decision to choose a different task than what the learners had been exposed to held merit due to learners getting the opportunity to transfer their prior knowledge and skills to a new, yet similar situation (Bransford, Brown, & Cocking, 1999; Kelley et al., 2014; Kelley & Sung, 2017). This implied that when I presented the learners with the design task from an unfamiliar textbook that was, however, semantically similar to their prior learning experiences obtained in the previous school term, I assumed that learning transfer could occur. As such, I carefully adapted the task in order to create one that was similar in scope to the tasks to which they had been exposed.

Adapting an existing textbook problem therefore seemed appropriate for three reasons. First, the problem reflected a design problem similar to those that the Grade 8 learners had already been exposed to in their classrooms at that point in time. Second, the existing textbook problem was based on the same topics of ‘structures’ and ‘processing’, and aimed to address pollution issues, which all of the participants had covered. Third, by using my own design, the participants could also be exposed to an unknown problem context where they had to apply their already mastered conceptual and procedural knowledge.

As the existing task that I selected focused on the application of technological and mathematical content knowledge, I had to add an element of scientific content knowledge in order for it to meet the criterion of being a STEM task (Capraro et al., 2016; Capraro et al., 2013). I therefore incorporated the concept of heat transfer into the design task. Subsequently, I changed the food from hamburgers to pap[2]. Refer to Appendix C1 to review the way in which I adapted the existing design task, as well as Figure 3.6, which indicates my main areas of concern on the right-hand side of the figure.

In addition, I adapted the existing design task due to the limited amount of information provided to the learners about the problem context in its original format, including, for example, only one picture about the environment in which the food items had to be sold. No pictures were included, for example, on the people involved, existing products that could be analysed, the environment in which the packaging would be used, or the types of food usually sold at taxi ranks. Knowing that the participants were novice designers (Lawson & Dorst, 2009), I realised that they would require external information on the problem context in order for them to effectively engage in problem structuring (Goel, 1995; Hubber, Tytler & Chittlebourough, 2018). Based on my understanding of Extended Design Cognition Theory (Haupt, 2015) and Activity Systems Theory (Engeström, 2015), I furthermore believed that Grade 8 learners may lack the necessary prior experiences to effectively solve a design task and would therefore require cognitive tools when attempting to solve ill-structured problems. I

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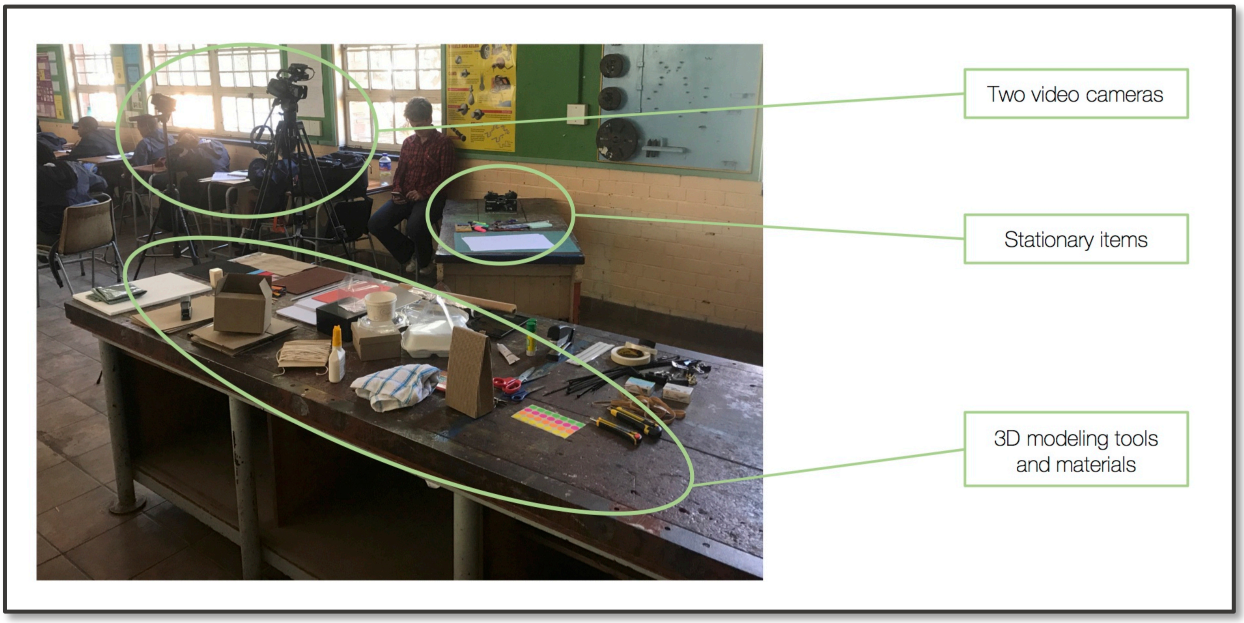
[2] Traditional indigenous South African starch dish made primarily from maize meal.

thus removed the task of designing and making recycling bins for the taxi rank (as required by the initial textbook design task) as it was not necessary for the purpose of this study.

3.5.2.3 Preparing the classroom environments for data generation sessions

During my final meetings with the teachers, we discussed how we could prepare the three classrooms for data generation as groups of learners required a space to engage in the STEM task. This involved a suitable space where they could understand the given problem; write their design brief, specification list and constraints list; generate design ideas; and physically construct models during idea generation. Subsequently, I set up a space in each of the three classrooms where the participants were able to sit down, plan, sketch, write, discuss and build models during the STEM task. Photograph 3.4 provides an example of one of the classrooms organised for the TAPS task.



Photograph 3.4: Classroom organised for the TAPS (Case B)

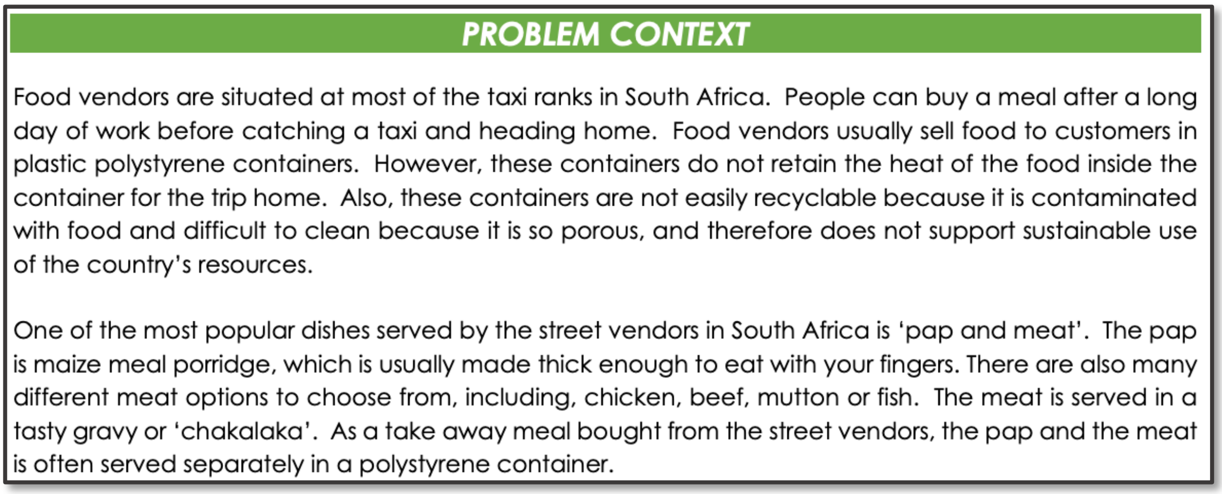
For data generation, each group of participants were provided with basic stationary items, including pens, pencils, safety rulers, post-it notes, coloured pencils, paper, paper clips, felt pens, and highlighters. In addition, I provided the participants with a range of tools and materials to use during the STEM task. In preparation for the data generation sessions, I unpacked all materials in order to ensure easy access and to limit disturbances to the participants' thinking processes. A list of the tools and materials that were provided for the STEM task is included in Appendix C2, which are also captured in Photograph 3.5.

Photograph 3.5: Stationary, tools and materials provided for the STEM task

As I relied on digital equipment to document my observations and the three data generation sessions, and in support of my prolonged engagement with the participants' thinking processes, I situated two recording devices in suitable locations in each classroom prior to commencement of the STEM tasks. I used one video-recorder to capture a wide-angle view of the TAPS environment, and employed a professional videographer to capture the narrow, microscopic events. An example of the set-up of the recording devices is captured in Photograph 3.4 (please refer back).

3.5.3 Final design task and stipulations

Following my adaptation of the textbook design task, I finalised the STEM task that I used for data generation purposes in the participants' interactions with social, conceptual and physical structures. The problem statement that I presented to the participants is depicted in Figure 3.7.



PROBLEM CONTEXT

Food vendors are situated at most of the taxi ranks in South Africa. People can buy a meal after a long day of work before catching a taxi and heading home. Food vendors usually sell food to customers in plastic polystyrene containers. However, these containers do not retain the heat of the food inside the container for the trip home. Also, these containers are not easily recyclable because it is contaminated with food and difficult to clean because it is so porous, and therefore does not support sustainable use of the country's resources.

One of the most popular dishes served by the street vendors in South Africa is 'pap and meat'. The pap is maize meal porridge, which is usually made thick enough to eat with your fingers. There are also many different meat options to choose from, including, chicken, beef, mutton or fish. The meat is served in a tasty gravy or 'chakalaka'. As a take away meal bought from the street vendors, the pap and the meat is often served separately in a polystyrene container.

Figure 3.7: Problem context and statement

I decided to use this problem statement as the basis for the design task in my attempt to study how the participants' design problem solving events emerged during the STEM task. As this problem statement is ill-structured, it required of the participants to engage in problem structuring in order to understand the context of the problem and to according formulate appropriate design objectives. In terms of a systems view on problem solving, this meant that I deliberately provided the participants with limited information in the problem statement, which in turn implied that they needed to search for other input information in order to structure their problem solving space (Goel, 1995). The participants therefore had to search, i.e. "investigate the background context, nature of the need, environmental situation, and people concerned" (Department of Basic Education, 2011, p. 49) using their design skills. This enabled me to collect data about how the participants in each case structured their design problem after providing them with a design opportunity, which is captured in Figure 3.8.

DESIGN OPPORTUNITY

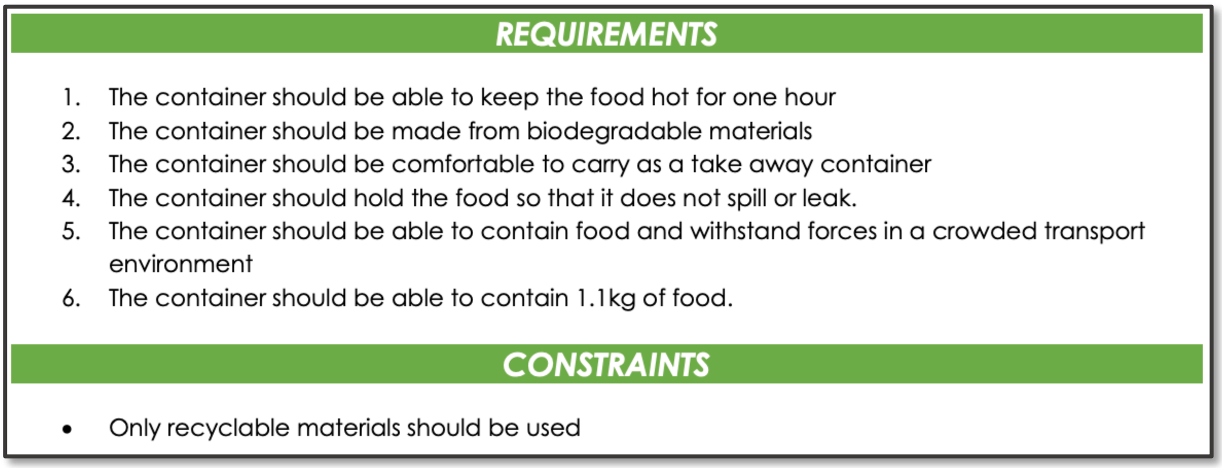
Design a recyclable heat retaining food container that will ensure that the pap and meat dish placed therein would retain its heat for at least one hour.

Figure 3.8: The design opportunity

The design opportunity guided the participants to design a 3D model of a recyclable heat retaining food container. For the design task, I did not disclose any information about how the food container should look, how it should work, or what it should be made of (Trebell, 2009). In this way, the participants' design events could emerge as a result of their own understanding of the problem and their interactions in the environment. I did, however, provide the participants with pictorial information about existing packaging designs (refer to Appendix C1) in an attempt to facilitate their awareness of prior knowledge and experiences with packaging from the previous school term's work. I also ensured that the design task complied with the requirements stipulated in the South African CAPS document for technology at Grade 8 level. I specifically aligned the design opportunity with the CAPS requirements by providing each group of participants with the design problem, which was embedded in a real-life context (Capraro et al., 2016). As a result, the learners investigated the problem context and design possibilities in completing the task.

The problem context namely involved food vendors selling food products in polystyrene containers that did not retain heat, and which polluted the environment. This provided the participants with a reason to engage in the design opportunity and to design a recyclable heat retaining food container that could ensure that the pap and meat dish it contained would retain its heat for at least one hour. This design opportunity seemed suitable as a STEM task since it provided the participants with a problem to solve by recognising an opportunity situated in a real-life context, which necessitated the use of scientific, technological and mathematical content knowledge (Capraro et al., 2016).

In order to guide the direction of the participants' thinking processes, I stipulated some design requirements and constraints, as captured in Figure 3.9. The purpose of these were to narrow the participants' ill-structured problem spaces, and to give them specific design issues to consider during the early phases of the design process.



REQUIREMENTS

1. The container should be able to keep the food hot for one hour
2. The container should be made from biodegradable materials
3. The container should be comfortable to carry as a take away container
4. The container should hold the food so that it does not spill or leak.
5. The container should be able to contain food and withstand forces in a crowded transport environment
6. The container should be able to contain 1.1kg of food.

CONSTRAINTS

- Only recyclable materials should be used

Figure 3.9: Design requirements and constraints

The design requirements and constraints furthermore implied that the participants had to possess the pre-requisite knowledge of scientific, technological and mathematical concepts. The pre-requisite knowledge and when learners had engaged with it prior to participating in this study is summarised in Table 3.6.

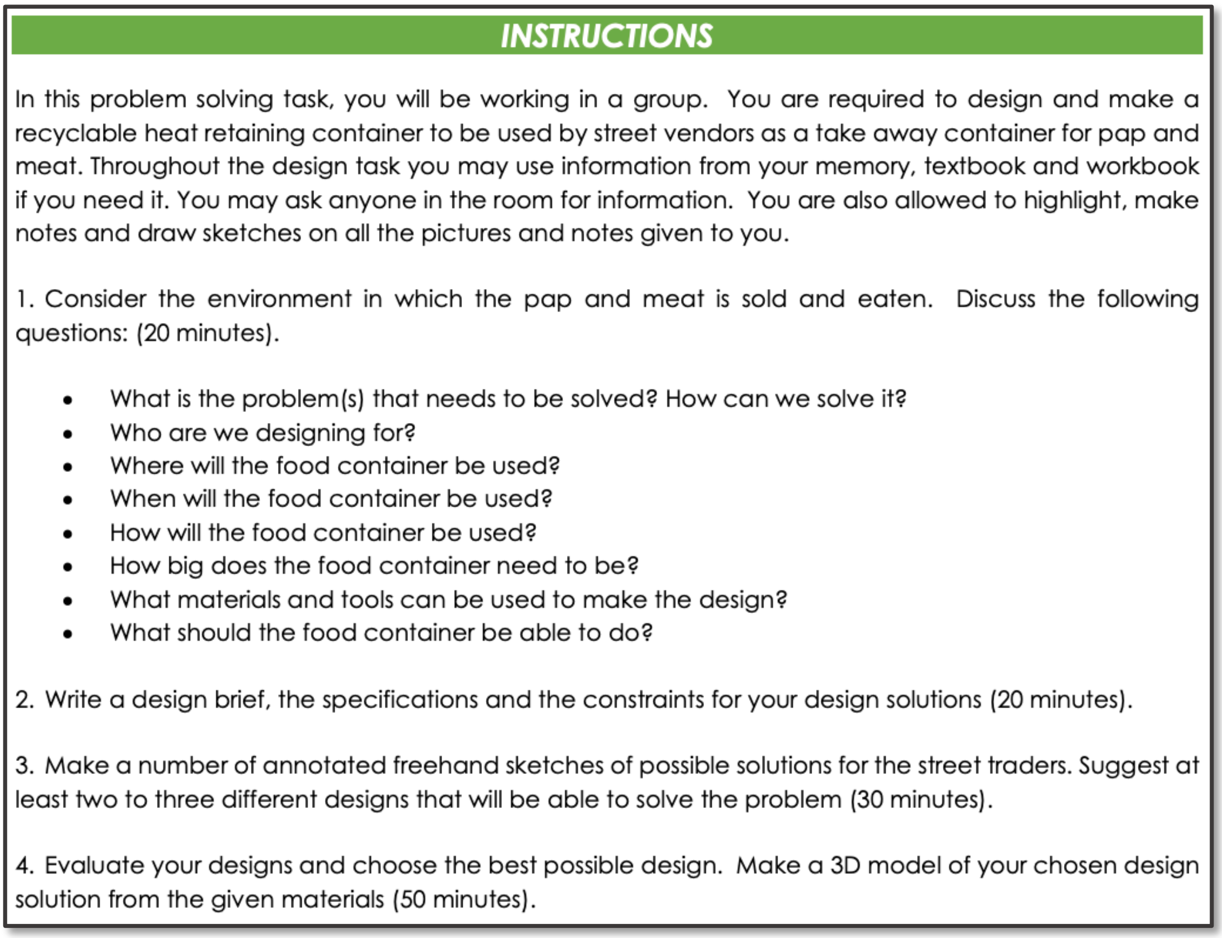
Table 3.6: Pre-requisite knowledge related to the design task

Subjects	Concepts	Covered in Grade …	Evidence
Science	Heat transfer	Grade 7, school term 3	DBE (2011, p. 27)
	Conduction	Grade 7, school term 3	DBE (2011, p. 27)
	Convection	Grade 7, school term 3	DBE (2011, p. 27)
	Radiation	Grade 7, school term 3	DBE (2011, p. 27)
Technology	Shell structures	Grade 4, school term 1 Grade 4, school term 2 Grade 4, school term 3 Grade 7, school term 2	DBE (2011, p. 22) DBE (2011, p. 26) DBE (2011, p. 28) DBE (2011, p. 16)
	Properties of materials	Grade 4, school term 2 Grade 5, school term 1 Grade 7, school term 4 Grade 8, school term 2	DBE (2011, p. 24) DBE (2011, p. 32) DBE (2011, p. 20) DBE (2011, p. 24)
	Recyclable material	Grade 6, school term 4 Grade 7, school term 3 Grade 8, school term 2	DBE (2011, p. 57) DBE (2011, pp. 18-19) DBE (2011, p. 24)
	Biodegradable material	Grade 8, school term 2	DBE (2011, p. 24)
Mathematics	Measurement: Length	Grade 4-6	DBE (2011, p. 25)
	Measurement: Mass	Grade 4-6	DBE (2011, p. 26)
	Measurement: Volume	Grade 4-6	DBE (2011, p. 26)
	Measurement: Perimeter, area and volume	Grade 4-6	DBE (2011, p. 28)

	Measuring surface area and volume of 3D objects	Grade 4-6	DBE (2011, p. 28)
		Grade 7 school term 2	DBE (2011, p. 56)
	Properties of 3D models	Grade 4-6	DBE (2011, p. 22)
	Building 3D models	Grade 7 school term 4	DBE (2011, p. 65)

Before formulating the design requirements and constraints, I ensured that the participants had already covered the concepts indicated in Table 3.6 in their prior schooling years. I consulted the respective curricula documents for the various subjects for this purpose, and confirmed in conversation with the three teachers that the participants would be able to use their specific scientific, technological and mathematical concept knowledge in the given design task. Despite these efforts, I was not able to ascertain in context that each of these concepts were taught to the individual participants during their schooling careers.

In order to further guide the thinking processes of the participants, I provided them with some structure by giving them a list of instructions. These instructions are captured in Figure 3.10. The purpose of the instructions was to guide the participants' attention to the various design objects that needed to be constructed during the design process. From an Activity Systems Theory viewpoint (Engeström, 2015), behaviours that emerge from working toward completing instructions can be viewed as object-oriented activities. These object-oriented activities were in turn guided by the rules of the activity system, as captured in the design problem statement.



INSTRUCTIONS

In this problem solving task, you will be working in a group. You are required to design and make a recyclable heat retaining container to be used by street vendors as a take away container for pap and meat. Throughout the design task you may use information from your memory, textbook and workbook if you need it. You may ask anyone in the room for information. You are also allowed to highlight, make notes and draw sketches on all the pictures and notes given to you.

1. Consider the environment in which the pap and meat is sold and eaten. Discuss the following questions: (20 minutes).

- What is the problem(s) that needs to be solved? How can we solve it?
- Who are we designing for?
- Where will the food container be used?
- When will the food container be used?
- How will the food container be used?
- How big does the food container need to be?
- What materials and tools can be used to make the design?
- What should the food container be able to do?

2. Write a design brief, the specifications and the constraints for your design solutions (20 minutes).

3. Make a number of annotated freehand sketches of possible solutions for the street traders. Suggest at least two to three different designs that will be able to solve the problem (30 minutes).

4. Evaluate your designs and choose the best possible design. Make a 3D model of your chosen design solution from the given materials (50 minutes).

Figure 3.10: Design problem statement instructions

I derived information for the instruction section based on my meetings with the senior technology teachers. My meetings with each of the teachers revealed that all of the participants had investigated a problem (instruction 1), formulated a design brief, specification list and constraints list (instruction 2), generated ideas by using freehand drawings (instruction 3) and evaluated and made models of design ideas (instruction 3) as part of their previous work. Furthermore, the instructions were also based on theoretical models of generic design processes (Dym et al., 2014) used by novice and expert designers. In order to determine a suitable time allocation for each instruction, I investigated teachers' guides and also asked the technology teachers for their opinions.

It should be noted that the instructions did not entail a prescribed sequence of actions for the participants to complete. The numbering of the instructions was merely to provide some structure to indicate the number of design outputs that were required for each design process. This was explicitly stated during my introduction to the TAPS environment on the day of data generation.

3.5.4 Data generation and documentation through TAPS

My choice of critical realism as paradigm implied that I engaged in extensive data generation and utilised multiple sources of data (Bygstad et al., 2016; Wynn & Williams, 2012). I used a TAPS methodology, allowing me to generate verbal, visual and temporal data, which could be analysed both qualitatively and quantitatively. This was done with the aim of uncovering the mechanisms underlying the participants' design problem solving events. Table 3.7 provides a brief overview of my data generation and documentation activities for each of the three schools/cases that I investigated, including all six groups of participants, even though I eventually only analysed the data of three groups.

Table 3.7: Overview of data generation and documentation activities

Case	Group	Participants	Date	Types of data generated	Duration of each TAPS
A	1	3 learners 1 Teacher	11 June 2017	– Video-recorded verbal utterances, interactions and gestures. – Temporal sequence. – Written design brief, specifications and constraints. – Design sketches. – 3D model of evaluated and chosen design.	2 hours
	2	3 learners 1 Teacher	12 June 2017		
B	1	3 learners 1 Teacher	10 August 2017		
	2	3 learners 1 Teacher	11 August 2017		
C	1	3 learners 1 Teacher	28 August 2017		
	2	3 learners 1 Teacher	29 August 2017		

In the following sub-sections, I discuss the data generation and documentation that I completed for this study in more detail.

3.5.4.1 Generating data during TAPS

TAPS is a strategy that is utilised to explicate the inherent thought processes of participants for analysis during problem solving or decision making activities (Ericsson & Simon, 1993). For this study, TAPS seemed suitable to generate evidence of the cognitive events that could be generated during participants' interactions with conceptual, physical and social structures. This strategy enabled me to access all three ontological levels suggested by the critical realist paradigm (refer to Section 3.2).

As a starting point, when applying the TAPS strategy, groups of participants are instructed to talk aloud while performing a given task and being video-recorded (Ericsson & Simon, 1993). By verbalising what they are thinking and doing, researchers can gain access to the sematic and syntactic structures of the participants' thoughts (Atman & Bursic, 1998; Smagorinsky, 1998; Van Someren et al., 1994). While the participants are talking, researchers thus capture the verbal utterances – usually by means of video-recordings, so that the participants' thinking processes can continuously be revisited in the sequence in which these occurred (Atman & Bursic, 1998; Jonson, 2003; Van Someren et al., 1994).

By providing the participants with an opportunity to create external representations that were documented, I was able to access both the internal and external structures with which the participants interacted, as well as the mechanisms that were activated to generate the cognitive events of the participants. Implementing a TAPS for data generation purposes thus allowed me to concurrently collect (i) verbal protocols of the participants' utterances, (ii) visual evidence of the participants' external representations, and (iii) a sequence of temporal instances of internal and external cognitive actions and events.

I used the design task discussed in Section 3.5.3 as an instrument to elicit the verbal, visual and temporal data generated by the participants. As I relied on a design task that complied with the requirements for ill-structured design problems, I was able to control the research environment to a certain extent by giving the same design task to different groups of participants, and providing each group with the same tools and materials. This means that I structured the research environment for each group in a consistent way and could strive for internal consistency. By providing each group of participants with the same STEM task, I did not in any way expect them to solve the STEM task in a similar manner, neither did I anticipate that each group of participants would generate the same solutions. These assumptions align with the critical realist stance that I took.

3.5.4.2 Documenting data generated during TAPS

Prior to recording each group of participants' process of design problem solving, I introduced myself and the research setting, allowing them to familiarise themselves with the video-recording equipment and the videographer. I allowed each group of participants to interact with the videographer that was present during the TAPS in an attempt to limit potential feelings of uneasiness which may have been caused by unfamiliarity. The videographer explained to the participants which seating arrangement would be best for optimal recordings and allowed them to also view the research setting through the lens of the video camera before commencing with any recordings. Prior to commencing with the study, I discussed ethical principles with the videographer, who subsequently signed a confidentiality agreement for conducting ethical research.

Even though the act of studying learners' behaviour while using video-recording devices may have some negative effects on their behaviour during research (Kazdin, 1998) – known as the Hawthorne effect (Holden, 2001) – these strategies assisted me in avoiding such negative effects. As such, I was able to plan for the potential "problem in field experiments that subjects' knowledge that they are in an experiment modifies their behaviour from what it would have been without the knowledge" (Adair, 1984, p. 334). To this end, by reducing the participants' feelings of uneasiness with the videographer, and allowing them to interact with the recording equipment (Haidet, Tate, Divirgilio-Thomas, Kolanowski, & Happ, 2009), I was able to limit the effect of these on their design activities. I also allowed each group of participants to interact with the available tools, materials and stationary items set up in the classroom beforehand, and to ask questions about unfamiliar tools and materials. These opportunities seemingly reduced their feelings of uncertainty.

The usability of TAPS for ill-structured teamwork activities in technology education has been debated in the past (Kelley & Sung, 2017; Trebell, 2010). Some scholars argue that language is merely a social representation of thought and does not necessarily mirror all thought processes in detail (Trebell, 2010). This implies that think aloud experiments are regarded as likely to provide poor representations of internal cognition and was therefore not an effective method to study participants' thoughts by this group of scholars. Others have furthermore opposed the use of TAPS with children based on researchers' perceptions that learners may possess limited developed verbalisation skills when compared to adults (Donker & Markopoulos, 2002).

For this study, I remained aware of these possible limitations of TAPS and as a result provided the participants with opportunities to use a variety of external representations of thoughts, including written notes, sketches, gestures and 3D modelling. I concur with Goldschmidt (2014), who states that verbal reports cannot provide a complete representation of designers' thought processes, even though they do provide some access to the thinking involved in designing, which would otherwise not be accessible. In order to enhance the participants' verbalisations, I requested them to work collaboratively in groups of three, and thus to mirror their natural classroom conversations, instead of providing individual descriptions of their thoughts.

3.5.4.3 Executing TAPS

The main instruction involved in any TAPS entails the request that participants say out loud whatever comes to mind while engaging in the given task (Ericsson & Simon, 1993). In this study, I extended this request to include participants' note making, annotations, sketches and 3D models. After requesting the participants to sit in their groups, I gave each group the following standard instruction:

> *"In a moment you will receive a task. I will read the task aloud, while you can read and make notes on your copy of the task. After I have read the task, you are allowed to ask any questions to me, your teacher, or the videographer. I would like you to complete the task in the way you would usually go about in your technology classroom. Please say aloud everything that you think so that your group members can hear what you are thinking about. The two cameras will focus on capturing your words as well as your sketches and 3D model making".*

After reading through the STEM task (refer to Appendix C1), I asked each group of participants if they had any questions. In traditional TAPS studies, the researcher's role is usually that of a restrained outsider, only interrupting participants' thinking processes when they need prompting to continue talking. However, as the participants in this study completed their STEM tasks in groups of three, the natural dialogue between the group members flowed easily, thereby enhancing the verbalisation of their thoughts.

After providing the participants with instructions, I proceeded to read the STEM task with them, making sure that they knew what was expected of them. Once I finished reading the STEM task and instructions, I asked whether or not the participants had any last questions before proceeding with their STEM task. After this last question, the participants were allowed to start interacting with each other and their problem statements in order to solve their design problems. Throughout the TAPS activity, I carefully observed the data generation activities and clarified any questions that arose.

As stated previously, I recorded each think aloud protocol on two video cameras – one stationary camera and one managed by the videographer, who captured each group of participants' voices, general movements and gestures, sketching, 3D modelling and writing. When the participants were walking and moving around to retrieve tools and materials, the videographer would follow them in order to capture all concurrent and verbal interactions. Although I was able to clear most of the background noise during editing, the recordings' audibility was affected at certain stages in the protocols, especially during the participants' 3D modelling activities. However, I was able to infer some missing visual information from the spoken words or sketches made by the participants. The video-recording process represented the first point of interface between the quantitative and qualitative data as the recording process captured moment-to-moment qualitative activities while simultaneously capturing the temporal measurement digitally.

3.6 DATA ANALYSIS AND INTERPRETATION

After collecting data through TAPS, I transcribed the verbal protocols and organised the visual data captured in each group of participants' sketches and 3D models. I transcribed the verbal protocols of each group into textual data, which I could analyse in a temporal sequence, as well as cross-reference with other external representations including gestures, sketches and 3D models. By typing out all the verbal utterances of each participant I was able to enhance the reliable coding procedures I employed (Jonson, 2003; Van Someren et al., 1994).

TAPS as a strategy typically generates large amounts of data. However, as Cash et al. (2015) note, not all of the generated data need to be immediately utilised as it merely forms the basis for a varied and multi-perspective reuse and reanalysis of data, implying the possibility of analysing different sections of the data at different times. As such, I adopted a streamlined approach in structuring and analysing the data that were generated by TAPS, following two phases. First, I structured and coded all qualitative data sources in terms of episodes, events and design moves, moving from the macro- to micro-levels of analysis (Ash, 2007) (refer to Appendix D1 and D2). After structuring and coding the micro-level data, which additional in-depth analysis, I relied on linkography to complete a focused quantitative and qualitative analysis as Phase 2 of the process.

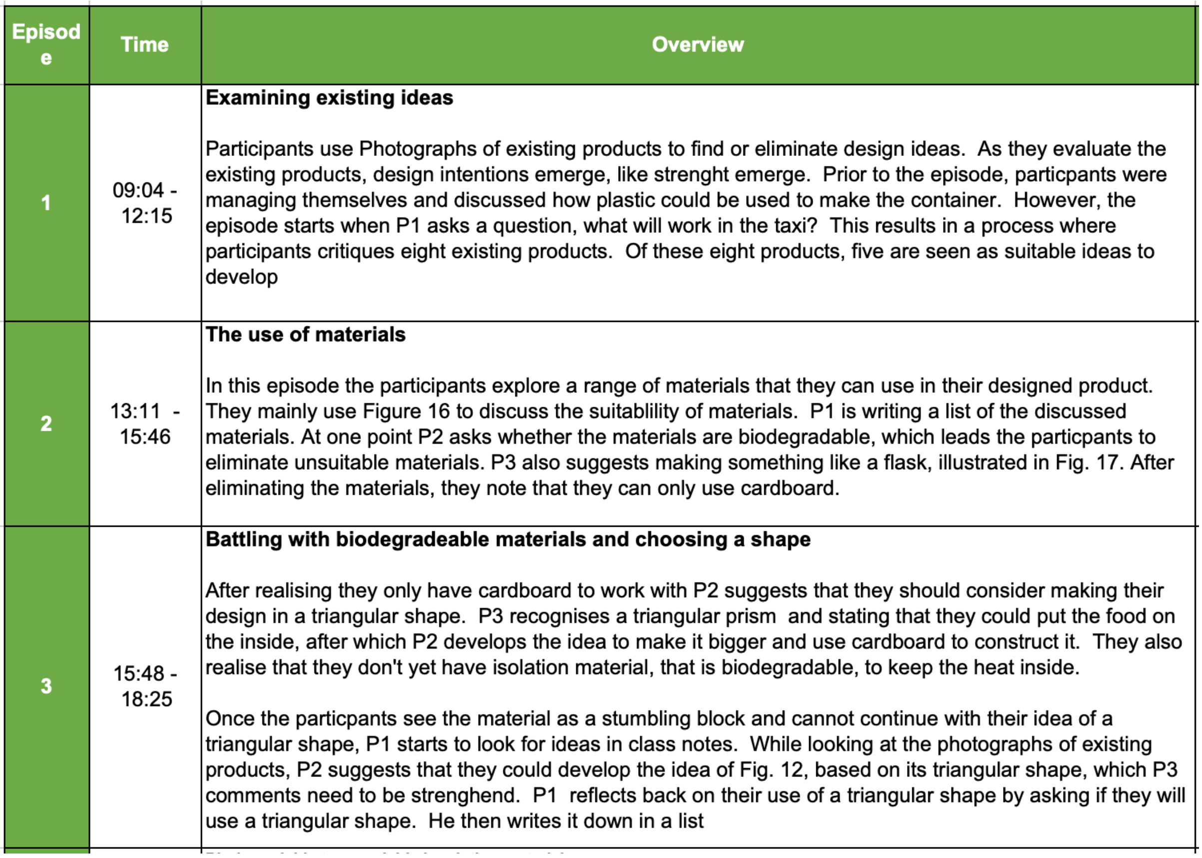
In preparation of my analysis, I structured both qualitative and quantitative data by identifying cognitive events and design moves during the participants' design processes. I furthermore structured the data by identifying the participants' generated cognitive phases and their modes of output. Visual data were also structured according to temporal data (refer to Appendix E2)

3.6.1 First phase macro-, meso- and micro-level analysis

The first level of structuring and analysis was guided by Ash's (2007) work, which allowed me to structure and analyse the verbal, visual and temporal data in terms of three levels of analysis, namely, macro-, meso- and micro-levels of analysis. Prior to engaging in the macro-level analysis, I immersed myself in the data by viewing the video-recorded data along with the transcripts of the verbal protocols multiple times. By viewing the video-recordings multiple times, I gained an overview of each group of participants' design process (Creswell & Plano Clark, 2018). This prepared me to analyse the data on a macro-level.

During the macro-level of analysis, I summarised each group's entire design process by creating a flow chart of design episodes that occurred, thereby creating three such charts. The flowcharts provided me with a large-grained, holistic overview of the design processes of the various groups (Ash, 2007). I was subsequently able to identify the episodes by means of inductive analysis (also referred to as content analysis or pattern analysis by Creswell and Plano Clark (2018). I did this by parsing episodes according to the participants' similar thought content. In this regard, I focused on making sense of the raw video-recorded data and transcripts by working with large amounts of qualitative visual and verbal data in order to identify design episodes embedded in coherent sequences of thoughts. In this manner, I was able to summarise the verbal and visual data into a broad sequence, placing specific sections of data within the wider design process (Patton, 2015). In addition, I made use of the quantitative temporal data to systemise the verbal and visual data into a sequence of episodes that could be further analysed. Figure 3.11 captures an example of my macro-level analysis structure.

Table 3.8: Macro-level analysis of the design processes



Episode	Time	Overview
1	09:04 - 12:15	**Examining existing ideas** Participants use Photographs of existing products to find or eliminate design ideas. As they evaluate the existing products, design intentions emerge, like strenght emerge. Prior to the episode, particpants were managing themselves and discussed how plastic could be used to make the container. However, the episode starts when P1 asks a question, what will work in the taxi? This results in a process where participants critiques eight existing products. Of these eight products, five are seen as suitable ideas to develop
2	13:11 - 15:46	**The use of materials** In this episode the participants explore a range of materials that they can use in their designed product. They mainly use Figure 16 to discuss the suitablility of materials. P1 is writing a list of the discussed materials. At one point P2 asks whether the materials are biodegradable, which leads the particpants to eliminate unsuitable materials. P3 also suggests making something like a flask, illustrated in Fig. 17. After eliminating the materials, they note that they can only use cardboard.
3	15:48 - 18:25	**Battling with biodegradeable materials and choosing a shape** After realising they only have cardboard to work with P2 suggests that they should consider making their design in a triangular shape. P3 recognises a triangular prism and stating that they could put the food on the inside, after which P2 develops the idea to make it bigger and use cardboard to construct it. They also realise that they don't yet have isolation material, that is biodegradable, to keep the heat inside. Once the particpants see the material as a stumbling block and cannot continue with their idea of a triangular shape, P1 starts to look for ideas in class notes. While looking at the photographs of existing products, P2 suggests that they could develop the idea of Fig. 12, based on its triangular shape, which P3 comments need to be strenghend. P1 reflects back on their use of a triangular shape by asking if they will use a triangular shape. He then writes it down in a list

Table 3.8 captures the format of the macro-level analysis that I completed for each group of participants. In the right column, it indicates how I noted thick descriptions of the episodes in my attempt to gain an in-dept understanding of each episode (Creswell & Plano Clark, 2018). Additional notes that I compiled during the macro-level analysis can be viewed in Appendix D3. By organising each group's design process into separate episodes, I was next able to engage in a deeper level of analysis, taking the form of meso-level analysis.

In this manner, the macro-level analysis that I completed provided me with a broad outline of the participants' design processes, which in turn enabled me to inductively identify significant design events during meso-level analysis. As such, I could engage in a finer grained analysis. In addition, I could see how design events arose from other design events, and how these subsequently affected future design events (Ash, 2007). An example of my analysis on the meso-level of the design events is captured in Table 3.9.

Table 3.9: Meso-level analysis of the design processes

Episode	Significant event	Time	Detailed context of utterances
Episode 1 *Examining existing ideas*	**1** *Searching and conjuring ideas from existing products*	09:47 - 10:38	During the first event the participants were guided by P1, who asked a question: *What would work in the taxi?* This question leads the participants to conjure up seven ideas by looking at photographs (Figures 6-11) of existing ideas in this event. While they are looking at the existing ideas, they evaluate each existing ideas. At idea #3, it is clear that P3 used 'strength of material' intention to evaluate idea #3, P1 use stability intention to evaluate idea #4 and P1 and P2 use 'strength of material intentions to evaluate ideas #5-6. In the final move, P1 justifies idea #6 because cardboard is hard and would therefore be strong enough in a taxi.
	2 *Understanding insulation material*	10:38 - 10:51	After proposing and evaluating ideas in event 1, P2 asks for a material that can serve as insulation for idea #6. This seems to point out the teams intention to keep the heat of the food inside the container, so that the food would remain hot for longer. This also suggest that they used scientific knowledge that insulation prevents heat transfer from occuring. To P2's question of finding insulation for idea #6, P1 proposes the use of plastic which could be wrapped around the outside of a container. P2 rejects this idea by stating that plastic will not insulate the container and propose aluminium foil instead - To which P3 elaborates that it should be on the inside of the container (Figure 10), not wrapped around like P1 suggested.

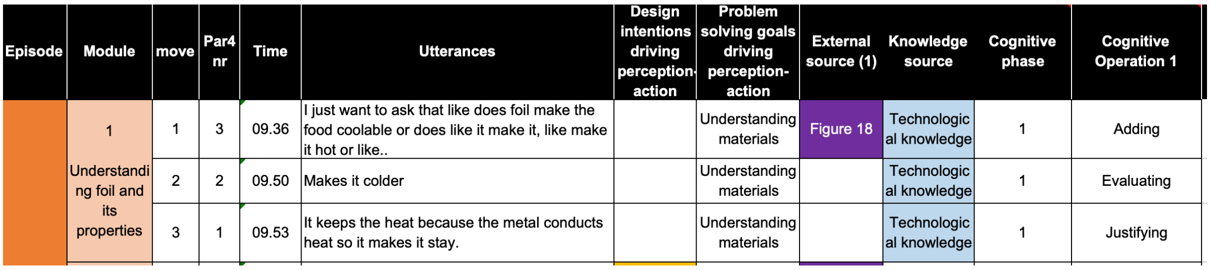
Table 3.9 illustrates how I further analysed each design episode identified during the macro-level analysis in terms of the design events, as well as each event's temporal instantiation. Each design event consisted of a recognisable beginning and end, as well as sustained conversational segments (Ash, 2007). In conducting the meso-level analysis, I was able to compile a thick contextual description of each design event, which allowed me to link design events with each other. Additional notes that I made during this level of analysis can be viewed in Appendix D4. By organising each group's design process into significant design events, I was able to engage in yet another deeper level of analysis during the following step, involving analysis on the micro-level.

In using the significant design events as an organising framework, I could next engage in fine-grained microscopic deductive analysis of all the design events using my conceptual framework as a guide (Patton, 2015). In preparation of deductive analysis, the transcribed protocols were segmented into smaller units of analysis, called design moves. According to Goldschmidt (2014, p. 30), a design move entails “a small unit of verbalization lasting a few seconds” and refers to “an act, an operation, that transforms the design situation somewhat relative to the state it was in before that move” (Ibid. p. 42). A design move may underpin a decision, or a tentative assertion; it may entail a question regarding an aspect of the emerging design; or it can involve a side comment or request for information (Goldschmidt, 2013).

A design move is thus commonly regarded as the smallest perceivable and coherent unit of operation that a participant will make during designing. In this regard, Goldschmidt (2013) notes that design moves will consist of segments ranging from a few words to a few sentences. In essence, design moves are microscopic steps, and are discernible from their contents. In analysing the data on this level, I regarded utterances such as “yeah”, “ok” and “mmmm” as meaningless in answering the research questions that apply to this study and therefore omitted these from the transcripts.

The purpose of segmenting the verbal protocol was to enable me to code each of the design moves according to an *a-priori* coding scheme (see Appendix D1), as described by Creswell (2014), as well as McMillan and Schumacher (2014). In order to maintain my focus during the structuring and coding procedures, I kept my purpose and research questions in mind and was guided by my conceptual framework. In the light of my conceptual framework, I catalogued *a priori* codes from existing theory. This enabled me to find effective ways to decompose the verbal data into discrete design moves that assisted me in examining the content and context of emerging problem solving processes. An example of the microscopic analysis that I completed is included in Table 3.10.

Table 3.10: Micro-level analysis of the design processes



Episode	Module	move	Par4 nr	Time	Utterances	Design intentions driving perception-action	Problem solving goals driving perception-action	External source (1)	Knowledge source	Cognitive phase	Cognitive Operation 1
	1 Understanding foil and its properties	1	3	09.36	I just want to ask that like does foil make the food coolable or does like it make it, like make it hot or like..		Understanding materials	Figure 18	Technological knowledge	1	Adding
		2	2	09.50	Makes it colder		Understanding materials		Technological knowledge	1	Evaluating
		3	1	09.53	It keeps the heat because the metal conducts heat so it makes it stay.		Understanding materials		Technological knowledge	1	Justifying

During the micro-level analysis, I commenced by identifying the exact points in the temporal data (quan) to which the participants' utterances (QUAL) related. Once I had matched the verbal utterances with the exact time of instantiation, I could start to apply my coding scheme. I coded the QUAL utterances based on the sequence of the design moves, the participant who produced the utterance, the design intentions, problem solving goals, external and internal information sources, cognitive phases, cognitive operations, physical actions and modes of output. Once the coding had been completed, I transferred the quantitative data to SPSS to be able to analyse the protocols in terms of frequencies, sequences, cross tabulations and distributions. In this way, I was able to explore, describe and explain the underlying cognitive mechanisms of the participants' design problem solving. After once again identifying micro-level level data that required an advanced level of in-depth analysis, I relied on linkography to complete a focused quantitative and qualitative analysis as Phase 2 of the data analysis and interpretation process.

3.6.2 Second phase linkography analysis

Linkography refers to a protocol analysis method that was first introduced by Goldschmidt (1990) to analyse the verbal protocols of individual architects (Goldschmidt, 1995) in order to assess their design productivity. This method has been implemented and researched by several scholars (Cai, Do, & Zimring, 2010; El-Khouly, 2015; Van der Lugt, 2005) in refining it for studies in design cognition (Gero & Kan, 2017; Hatcher et al., 2018; Roozenburg, 2016). However, linkography has not yet been established as a strategy that can be utilised when doing research with learners in the field of design and technology or STEM education. As such, my study holds the potential of adding knowledge to this relatively new and emerging methodological strategy.

3.6.2.1 Linkography as data analysis strategy

Linkography enables researchers to visually represent and analyse individual or teams of designers' processes of designing. Essentially, each linkograph represents the chronology of connections that designers make between their thoughts, which will subsequently result in design ideas. These connections can then be analysed both qualitatively and quantitatively (Gero & Kan, 2017; Goldschmidt, 2014).

Linkography has been utilised in several professional design contexts to understand the complexity of designers' thought processes during designing. Examples of existing studies include those that focus on how design ideas are conceptualised and developed (Goldschmidt, 1995) on the nature of design reasoning in the early phases of the design process (Goldschmidt, 2013), the role of sketching during idea development (Van der Lugt, 2005), the role of team communication during designing (Jiang & Gero, 2017), and uncovering moments of creative discovery during designing (El-Khouly, 2015), to mention but a few.

In comparison to other methodologies used in design studies, linkography allows researchers to investigate the ontological nature of design processes rather than merely describing designing in terms of design activities or phases (Goldschmidt, 2014; Haupt, 2018). Linkography can furthermore enable researchers to uncover the basic structure of reasoning involved in designing (Goldschmidt, 2014). I selected linkography due to my purpose of gaining insight and an in-depth understanding of how learners' incremental interactions with social, conceptual and physical interactions engendered their thought instantiation during designing. In this way, linkography did not only enable me to investigate the participants' mediating states exemplified in Extended Design Cognition Theory (Haupt, 2015) – which I adopted as part of my conceptual framework. It also allowed me to trace these interactions with the social, conceptual and physical structures as emphasised by Activity Systems Theory (Engeström, 2015).

3.6.2.2 Constructing a linkograph

When generating a linkograph, verbal utterances are segmented into a chronology of 'design moves'. According to the Extended Design Cognition viewpoint (Haupt, 2015), moves represent the different mediating states in the Extended Problem Solving

Space. In order to segment a verbal protocol into design moves, I parsed the verbal utterances based on the participants' turn-taking, which is a common segmenting principle in team designing (Gero & Kan, 2017; Goldschmidt, 2014; Hatcher et al., 2018).

After segmenting verbal protocols into a sequence of design moves, a linkograph can be made by identifying the links between the various design moves (Goldschmidt, 2016). All the links made in a linkograph are backlinks, as the moves link to previously generated design moves (Goldschmidt, 1990). Once the backlinks have been formed for a design session, one can retroductively speak about a forward link[3] between an earlier move and a move made later in time. There is a distinct difference between forelinks and backlinks. More specifically, a backlink of a design move records the path that led to its generation and can be determined at the time the move is made (Goldschmidt, 1990). A forelink typically bears evidence of its contribution to the production of further moves and can only be established after the backlinks have been established (Goldschmidt, 1990).

Although Goldschmidt (2014) notes that the link-coding process is based on a 'common sense' approach, as well as an understanding of the domain in which the design process is embedded, I followed the guidelines of Hatcher et al. (2018) for link-coding. These guidelines guided me to make a link between two design moves when participants directly related their thoughts or actions to earlier thoughts in the protocol; or where visible hand gestures, sketching, 3D modelling or writing related to earlier thoughts; or where structural, functional or behavioural (semantic) similarities between thoughts occurred; or where the design moves occurred in serial and were within the same chain of thought.

In order to quantitatively explore the links between design moves, Goldschmidt (2014) uses a link index. As such, a link index is a quantitative measure used in linkography to indicate the interconnectedness of thoughts. The link index is calculated by dividing the number of links by the number of design moves. This means that a link index represents the ratio between the number of links and the number of moves that are

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[3] Throughout, I use the terms 'forward link' and 'forelink' interchangeably. Similarly, I used 'backward link' and 'backlink' as synonyms.

analysed. Goldschmidt (2014) explains that a link index can provide a quick indication of the extent of linking activity in a design episode, which in turn can give an indication of the designer's efforts to achieve a sound synthesis. Goldschmidt (2014) furthermore notes that productive designers will only elicit design moves with a high potential for connectivity to other moves, which is represented by a high link index, as opposed to less productive designers who will typically elicit unconnected ideas at random, thereby resulting in less links.

3.6.2.3 Types of design moves

Figure 3.11 illustrates the general structure of a linkograph and the types of design moves that can be captured and illustrated. Goldschmidt (2014) distinguishes between four primary types of design moves, namely, orphan moves (move 10 in Figure 3.11), unidirectional moves (moves 1, 2, 3, 5, 6-9, 11-12), bidirectional moves (move 4) and critical moves (move 4).

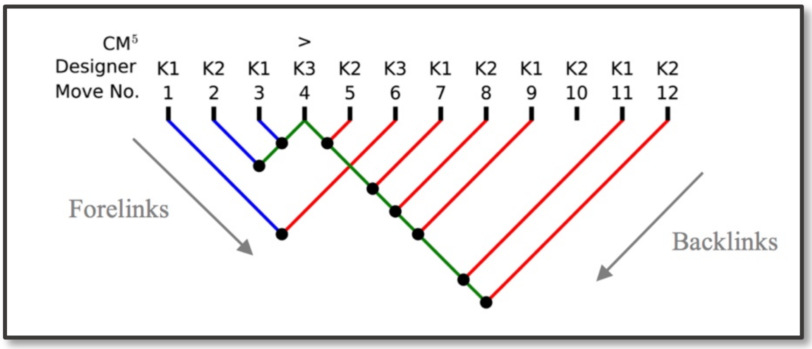


Figure 3.11: General structure of a linkograph

Orphan moves are isolated moves that are not related to any of the other design moves. Based on her research, Goldschmidt (2014) is of the view that novice designers are more likely to create orphan moves in comparison with expert designers. She explains that a possible reason for the fewer orphan moves in expert design protocols relates to experts being able to anticipate the implications of their moves for longer stretches of future moves. Next, unidirectional backlink moves imply that, at the moment of their instantiation, a participant was concentrating on what had transpired up to that point (Goldschmidt, 2014), without any reference to future design moves. In contrast, unidirectional forelink moves imply that a participant was instantiating a new thought that did not refer to previous thoughts or what had been done (Goldschmidt, 2014).

Moves that contain both backlinks and forelinks are labelled as bidirectional moves. In Figure 3.11, move 4 backlinks to moves 3 and 2, but also forelinks to moves 5, 7, 8, 9, 11 and 12. Bidirectional moves thus suggest that designers are planning ahead while still making sure that continuity is maintained between past design moves (Goldschmidt, 2014). Bidirectional moves illustrate how participants may rapidly move between two modes of thinking, being divergent and convergent thinking (Goldschmidt, 2016).

Finally, critical moves are design moves that are rich in links in comparison to other moves and can be unidirectional or bidirectional. In order to identify critical moves, a threshold number of links per move needs to be determined. The criteria for determining critical moves will vary depending on the context of a study, however, Goldschmidt (2014) advises that the criteria should allow for 10 to 12% of the moves with the highest number of links of the total number of moves to be classified as critical moves. In linkography, critical moves are seen as significant as they indicate a high level of interconnectivity between moves, which will typically result in synthesis in design (Goldschmidt, 2016). If a design move, for example, has a high number of backlinks, it means that the move referred back to a great deal of previous design moves, implying that new thoughts that were proposed were developed, explored or summarised. Similarly, a design move with a high number of forelinks suggests that the move was an important new thought that emerged during designing, and was critical in the development of the overall thought process of the designers.

3.7 QUALITY CRITERIA

I aimed for rigour by adhering to Babbie and Mouton’s (2006) guidelines for quality assurance in conjunction with measures for quality assurance in case study research designs, as postulated by Yin (2018). Throughout, I attempted to ensure credibility, transferability, confirmability, dependability and authenticity. In addition, I used inter-rater reliability measures in order to enhance the quality of my linkography analysis.

3.7.1 Reliability of linkographic analyses

In order to enhance the reliability of the link coding, I used inter-coder reliability (Gero & Kan, 2017; Salman et al., 2014). This enabled me to ensure the coding consistency of the links between design moves at two different coding intervals (Salman et al., 2014). For this purpose, I calculated the percentage of agreement between the two coding intervals that I carried out two weeks apart. I thus calculated an agreement percentage for the coded protocol by computing the agreement percentage of the coding between the first and second coding session. Finally, after the second coding session, I asked another researcher to also code the links between the design moves. After this third coding session, which was done by another researcher, we compared the observed discrepancies between dissimilar codes and had a discussion to select the most reliable one. In Table 3.11, I summarise the coding consistency between the different coding sessions.

Table 3.11: Consistency between coding sessions

Design moves	1st and 2nd session (%)	3rd arbitrated coding (%)
Case A		
1-50	83.62	87.45
51-100	79.36	84.93
101-150	76.40	81.28
151-200	81.44	87.98
201-250	81.18	88.36
251-300	79.32	83.34
301-350	80.59	85.89
351-393	91.23	94.23
Average	**81.64**	**86.68**
Case B		
1-50	82.20	85.86
51-100	84.67	88.43
101-160	81.32	86.92
Average	**82.73**	**87.07**
Case C		
1-50	78.48	84.31
51-100	81.82	86.20
101-150	76.28	82.04
151-200	82.88	87.69
201-231	91.32	96.73
Average	**82.16**	**87.39**

For the first comparison between the first and second coding sessions, the comparison between codes in all three cases yielded a coding consistency average of more than 80% respectively. After the third session, the average coding consistency increased to more than 85% for all three cases. These results are consistent with previous studies employing linkography who reported coding consistency percentages between

70% and 94% (Atman, Chimka, Bursic, & Nachtmann, 1999; Gero & Kan, 2017; Salman et al., 2014).

3.7.2 Credibility

Credibility in this study referred to the degree to which I was able to identify the presence or absence of social, cognitive and physical structures, mechanisms and events, and the relationships among these ontological concepts (Yin, 2018; Lincoln & Guba, 1985). Furthermore, credibility relates to the believability of my interpretation of such ontological concepts and the way in which I explained their causal relationship with the participants' design choices (Yin, 2018; Lincoln & Guba, 1985).

I implemented several strategies in an attempt to enhance the credibility of this study – throughout the processes of data generation, documentation, analysis and reporting. Firstly, I engaged in continuous observations of the verbal utterances, writings and visual drawings, 3D models and gestures as captured through video-recordings (Babbie & Mouton, 2006; Yin, 2018). Capturing each group of participants' design processes by means of video-recordings allowed me to repeatedly watch the recordings in an attempt to ascertain the context of the participants' cognitive events and interactions. The credibility of the inferences that I made about the social, conceptual and physical structures, mechanisms and events underlying the participants' design problem solving was thus directly dependent on meticulous re-examination of the verbal and visual data sources while constantly testing interpretations against the conceptual framework of this study (Ericsson & Simon, 1993). As such, I was able to credibly document and analyse verbal and visual data in the contexts of the occurrences, since verbal data could not indicate what the participants gazed at or pointed towards, or which sketches the participants were speaking of. Additionally, video-recordings allowed me to systematically to transcribe the verbal data by utilising the slow speed playback option (Cohen, Manion & Morrison, 2011).

Secondly, I strived to ensure the credibility of the interpretation of my results by repeatedly engaging with the senior technology teachers of the three schools prior to commencing with the data generation sessions. During this engagement, I was able to gain insight into the Grade 8 work that had been completed at the time, how each of the teachers had facilitated design projects in class, and which learning materials each school were using in their science, mathematics and technology classrooms. This background information enabled me to compile thick descriptions about the context of each case in finalising my research report.

Finally, in subscribing to critical realist assumptions, I generated multiple types of data, thereby ensuring data triangulation which could enhance the credibility of my findings (Creswell & Plano Clark, 2018; McMillan & Schumacher, 2014). Cohen et al. (2011) explain that data triangulation represents a researcher's attempt to increase the richness of findings by studying data from more than one viewpoint. For my data generation, I focused on three data types, these being verbal, visual and temporal data, as necessitated by my conceptual framework. I furthermore transformed qualitative data into quantitative frequencies, sequences and distributions, which once again enabled me to engage in deep levels of analysis. As such, I was able to analyse each group of participants' design problem solving processes in terms of the underlying social, conceptual and physical structures, mechanisms and events. I did this by studying their external representations. In this manner, I was able to enrich my findings by describing each group's cognitive events and interactions from various data types. Moreover, I was able to enhance the credibility of my own interpretations by cross-referencing between the data sources. This means that I continuously made interpretations based on my observations of the verbal, visual and temporal data.

3.7.3 Transferability

Transferability refers to the applicability of a study's findings to other contexts (Lincoln & Guba, 1985; Babbie & Mouton, 2006). Although I acknowledge that the purpose of this study was not to generalise any findings, I anticipate that the insight I gained from studying the three selected cases may contribute to an understanding of some of the potential structures and mechanisms underlying learners' design problem solving processes. These structures, mechanisms and events may thus occur in other South African classroom contexts, meaning that the findings may be transferrable to similar school contexts, even though I do not make any such claims.

In order to enhance the transferability of my study, I include a description of each of the three cases under study (Babbie & Mouton, 2006; Yin, 2018). To this end, I collected sufficient information about the context and conditions in which the participants engaged in design problem solving in order to allow the reader to decide whether or not the findings of this study, and to what extent, can be transferred to similar contexts. In addition, as I used purposive sampling techniques (Guba & Lincoln, 2005), I could specify the boundaries of my cases and state that I only involved Grade 8 learners in medium-resourced schools as participants. Finally, I declared the theoretical underpinnings of this study throughout this thesis, allowing me to stay within the theoretical boundaries and enabling other researchers to decide how the findings of this study may fit into the broader body of theory on design cognition.

3.7.4 Confirmability

Confirmability refers to the degree of neutrality with which the data analysis is approached and completed (Babbie & Mouton, 2006; Yin, 2018). Confirmability therefore implies that data will relate to the findings of a study in an unbiased manner (Suter, 2012). From the start of this study, I acknowledged my own biases and remained aware of these throughout the study and data analysis. I endeavoured to present the data and my interpretations thereof as truthfully as possible, and as closely linked to the theoretical underpinnings of this study. I also followed Yin's (2014) recommendation to compile thick descriptions in order to convey the findings in such a way that these clearly relate to all three cases.

I furthermore attempted to enhanced the confirmability of my interpretations and findings by including a confirmability trail in this thesis (Babbie & Mouton, 2006), thereby allowing the reader to determine whether or not my conclusions, interpretations and recommendations can be traced back to the raw data. The need for a confirmability trail resulted in my inclusion of evidence of the data generation, documentation, analysis, interpretation and reporting practices that I completed (Babbie & Mouton, 2006). My audit trail consists of raw data in terms of the video-recorded verbal protocols, transcripts and visual representations in the form of sketches and 3D models, which I include as appendices. In addition, I include examples and evidence of my data reduction and analysis procedures and products. In Chapters 3 to 5, as well as in the appendices, I also provide the final STEM task that was given to each of the three cases.

3.7.5 Dependability

I regarded the findings of my study as dependable as I believe that my findings are consistent and repeatable (Lincoln & Guba, 1985; Babbie & Mouton, 2006). My decision to video-record the thinking processes of each group of participants was based on my attempt to ensure a high degree of reliability when coding the data. For this purpose, I utilised an inter-coder reliability technique, i.e. a reliability technique in which corresponding codes can be found by two different coders in the same data set (Van Someren et al., 1994). In this manner I attempted to enhance the dependability of this study by asking another researcher in design cognition to independently code ten samples of verbal utterances, using the same coding scheme and theoretical understanding. The consistency of the agreement between myself and the second coder was determined by using the following formula (Jackson, 2006, p. 61):

$$\text{Inter-rater reliability} \quad \begin{aligned} &= \frac{\text{Number of agreements}}{\text{Number of possible agreements}} \text{ X } 100 \\ &= \frac{80}{100} \end{aligned}$$

A review of the second coder’s classification revealed that the small disagreement noted above (20%) could be attributed to the fact that cognitive phases or events are not always clearly distinguishable (Goel, 1995; Restrepo & Christiaans, 2004). In this regard, Stemler (2004) suggests that values ranging from 75% to 100% demonstrate a satisfactory level of dependability when determining inter-rater reliability based on the percentage of absolute agreement. Establishing an agreement between the two sets of codings embedded in the conceptual framework of this study however seemed to have resulted in dependable inferences.

3.7.6 Authenticity

Authenticity in this study refers to whether or not the results and findings provide a true description of the participants, contexts and events (Lincoln & Guba, 1986). In order to enhance the authenticity of this study, I attempted to immerse myself in the participants’ worlds through prolonged engagement with the video-recorded data. As such, I was able to develop an in-depth understanding of the cases. I presumed that the participants' generated thoughts and ideas during TAPS were rational and relevant according to their understanding, and I therefore accepted them as authentic. Furthermore, I attempted to portray the multiple realities of the three groups of participants in a true-to-life way (Creswell, 2014; Lincoln & Guba, 1986).

3.8 REFLECTING ON ETHICAL GUIDELINES

Due to the age (±13 to15 years) of the participants, I sought permission from the various relevant stakeholders in order to ensure that my research was conducted in accordance with the guidelines for undertaking ethical research with human participants. I namely obtained permission to conduct this study from the Ethics Committee of the University of Pretoria's Faculty of Education, and from the Gauteng Department of Education's provincial district office. Based on the stipulations of the DBE permission, I conducted all data generation sessions after school hours at the respective schools. I took the necessary care to maintain a naturalistic learning environment in which the participants could interact with social, conceptual and physical structures as they normally would during class.

Next, I sought permission from each of the three school principals (Appendix A3) and the respective School Governing Bodies where the research was to be conducted (Appendix A4) as well as the three senior technology teachers in whose classes I video-recorded the STEM tasks (Appendix B1). I also sent informed consent letters to the parents of the learners participating in the research study (Appendix B2) outlining the nature of the study and implications for their participation. Finally, I obtained learner assent after explaining the nature and scope of the study to the participants (refer to Appendix B3). During the processes of obtaining informed consent/assent, I explicitly stated that participation in the research study was voluntary and that the participants had the opportunity to withdraw at any stage without any negative consequences (Babbie & Mouton, 2006; Cohen et al., 2011).

Throughout my study, I respected the safety of the participants. As such, the participants were not placed in any situation where they could have been hurt – either physically or emotionally. I also ensured that the participants were at ease during the TAPS procedures by providing them with the chance to explore the tools and materials as well as the recording devices before participating in the STEM design task. I allowed them to ask questions whenever they experienced the need to do so. Closely related, I attended to maintaining relationships of trust with the participants by not subjecting them to any acts of deception or betrayal during the research procedures or published outcomes (Babbie & Mouton, 2006; Cohen et al., 2011).

I respected the participants' privacy by means of confidentiality and anonymity (Babbie & Mouton, 2006; Cohen et al., 2011). I did this by omitting their real names and using pseudonyms, such as P2, when referencing their cognitive actions of specific participants during the STEM task in both the transcripts and when reporting verbal and visual data. As stated earlier, the videographer was also briefed to respect ethical guidelines throughout the study.

Finally, the raw data that I generated during the TAPS procedures are stored in a locked cabinet at the University of Pretoria for 15 years. In this way, the identities of the participants will remain protected. Throughout this study, the data were only available to the external coder and my supervisors, and not disclosed to anyone else.

3.9 CONCLUSION

In this chapter I described the empirical study that I undertook and completed. I explained the critical realist paradigm in which my study is embedded and justified the use of my research design, data generation and documentation methods, as well as the data analysis and interpretation procedures. I concluded the chapter by explaining the quality measures that I adhered to and the ethical principles that I respected.

In the next two chapters I present the results of my study. In Chapter 4, I more specifically focus on the general linkography results and the participants' interactions with social and conceptual structures. This discussion is followed by my presentation of the results on the nature of the participants' interactions with physical structures in Chapter 5. Throughout, I relate the results that I obtained to existing literature, thereby foregrounding the findings I obtained.

CHAPTER 4

GENERAL LINKOGRAPHY RESULTS AND FINDINGS ON SOCIAL AND CONCEPTUAL STRUCTURE INTERACTIONS

4.1 INTRODUCTION

In Chapter 3 I described the research methodology of this study. I explained and justified all the methodological choices that I made against the background of the research questions and the purpose of this study, as well as the conceptual framework that guided me in undertaking this investigation.

In this chapter, I present the results of the study, specifically in terms of the general thought patterns that could be identified during the participants' design processes, illustrating these results in terms of the various linkographs created for the three groups of participants. I also present the results I obtained on the social interaction patterns, as well as their interactions with conceptual structures. In my presentation of the results obtained, I refer to existing literature in the field throughout in order to discuss my findings.

4.2 GENERAL LINKOGRAPH RESULTS

In this section, I present and discuss the linkographs generated for the respective groups of participants. For this purpose, I first summarise each of the linkographs in terms of the number of design moves, number of links and link indexes, and then proceed to discuss the cognitive phase events that emerged during each group's design process. Finally, I summarise and discuss the number and types of design moves that were generated by each group of participants.

4.2.1 Linkographs of the three cases

Figures 4.1 to 4.3 capture the linkographs that were generated for the design sessions of each group of participants.

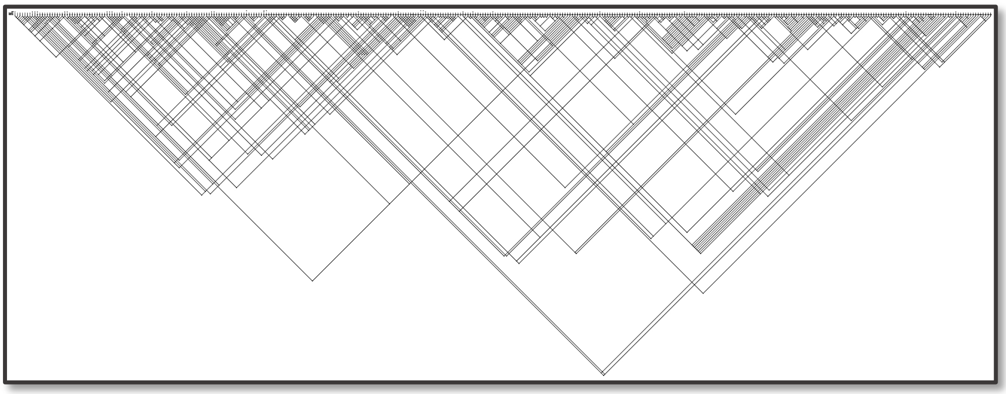


Figure 4.1: Linkograph of Group A (Case A)

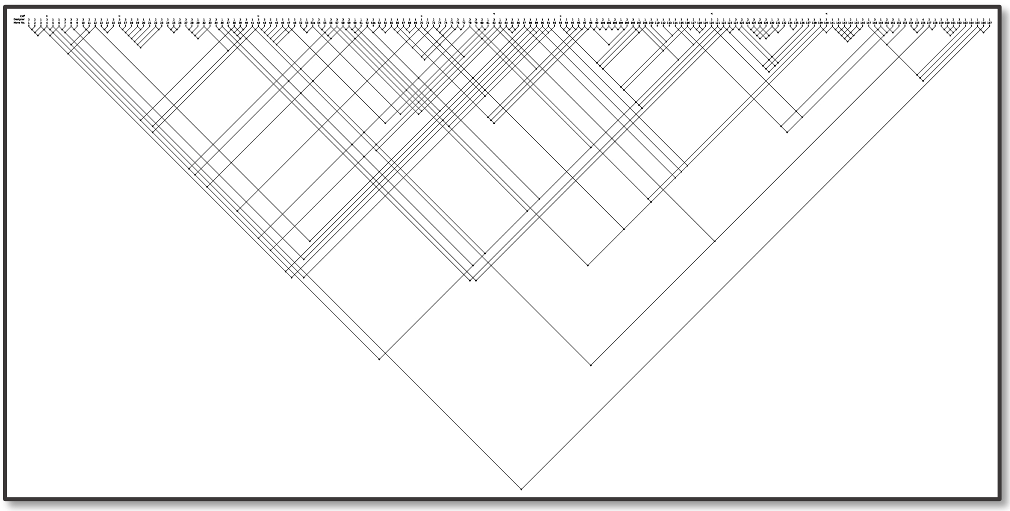


Figure 4.2: Linkograph of Group B (Case B)

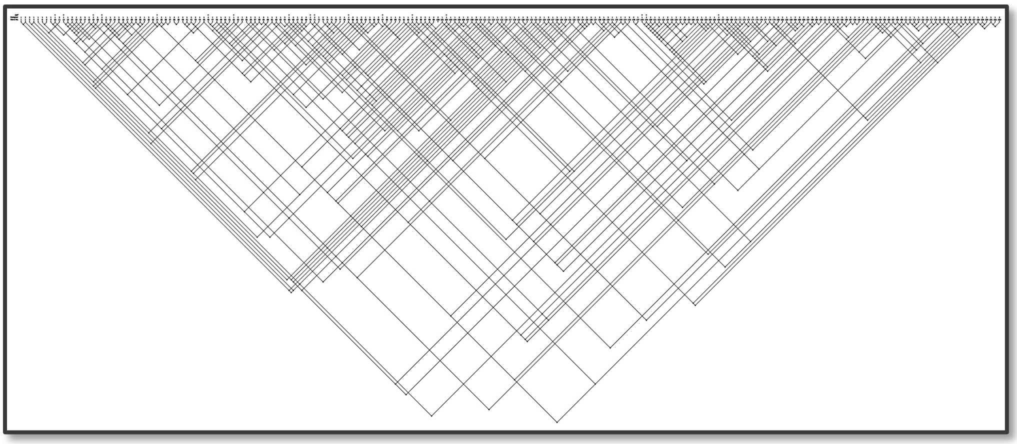


Figure 4.3: Linkograph of Group C (Case C)

At first glance, it is clear that each of the linkographs indicates a distinct interconnectedness between the participants' thoughts in each of the teams as they progressed in the design process. In addition, it is possible to observe the definite difference in the number of backward and forward links between the various linkographs generated by the respective groups. Upon closer inspection, the quantitative results, as captured in Table 4.1, indicate that a significant difference exists in the number of design moves generated by each of the group of participants.

Table 4.1: Number of design moves, links and link index for the three groups

	Group A	Group B	Group C
Number of design moves	393	160	231
Number of links	893	247	527
Link index	2.3	1.6	2.3

The data in Table 4.1 reveal a range in the number of design moves that were generated by the various groups of participants. Group A and Group C generated the most design moves, with Group B generating less. The same trend applies to the number of links that were generated by the various groups of participants, with Group A generating the most forward and backward links between moves. On the other end of the spectrum, Group B generated the least number of links. This result could be related to the lower number of design moves that were generated by Group B, with the total number of design moves positively correlating with the number of links in all three cases.

Furthermore, when comparing the link indexes of the different groups' linkographs, Group A and Group C had more productive design sessions than Group B. When employing linkography, the link index provides a measure of how connected the participants' design moves are in a design session. In order to calculate the link index in an overall session, the total number of links is divided by the total number of moves in the design session (Goldschmidt, 2014). Therefore, both Groups A and Group C had a link index of 2.3, which means that, on average, each generated design move linked backwards or forwards to two or more design moves in the case of these two groups. Alternatively, for Group B, the generated design moves linked backwards or forwards to only one or more design moves.

4.2.2 Cognitive phase events underlying the design moves

In order to further understand the differences between the number of design moves generated by the various groups of participants, I investigated the cognitive phases underlying the participants' design moves. Figure 4.4 represents the cognitive phase events of the three groups.

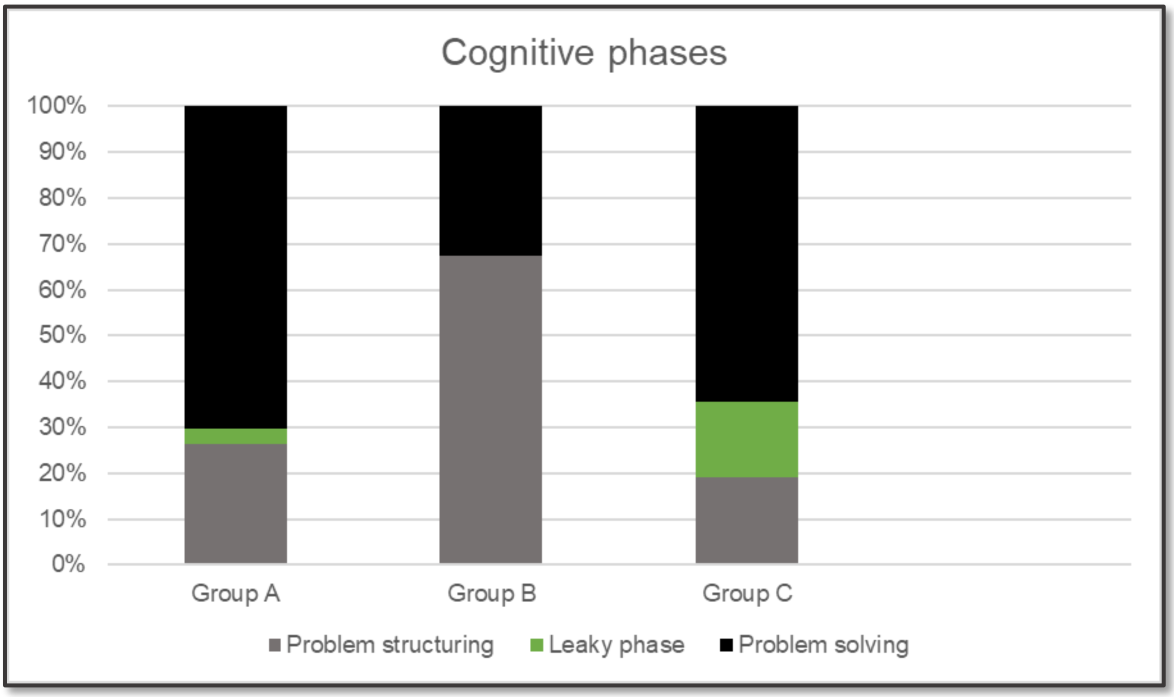


Figure 4.4: Cognitive phase events of the three groups

From Figure 4.4, it seems evident that the majority of Group A's (70%) and Group C's (64%) generated design moves were embedded in problem solving cognitive phases, while the majority of Group B's (68%) design moves were generated during the problem structuring cognitive phase. This implies that, during the design session, the majority of Group B's design moves were aimed at understanding the problem and the design context instead of finding and developing solutions. On the contrary, the majority of the design moves by the participants of Groups A and C focused on finding solutions.

Existing studies on learners' design cognition (Kelley et al., 2015; Strimel, 2014) during the early phases of design indicate similar findings. More specifically, these authors also found that the majority of school learners will engage in cognitive processes related to preliminary problem solving rather than the processes concerning the understanding and defining of a design problem. Furthermore, literature on professional design behaviour (Lawson, 2006; Lawson & Dorst, 2009) indicates that expert designers will tend to focus the majority of their time on design solutions, whereas novice designers generally spend most of their time on understanding the design problem. Based on the results on the cognitive phase events of the participants of this study, Groups A and C thus aligns with the performance of expert designers, while Group B seemingly operated on a novice designer level.

The difference between Groups A and C on the one hand, and group B on the other, may potentially be ascribed to the fact that School B was the only school situated in a low socio-economic area. This implies the possibility of the participants not possessing the same level of prior knowledge and life experience of the learners in Schools A and C. As a result, the participants in Group B might have spent more time on understanding the problem than on directly moving into finding solutions. This is however, a mere working assumption, which requires more research in order to be able to reach a clear finding.

Another possible explanation for the dominance of problem solving events in comparison to problem structuring events can furthermore be related to the nature of the STEM task that I presented to the participants. As discussed in Chapter 3, I adapted the STEM task from a prescribed textbook for Grade 8 technology. The instructions of the STEM task seemed to primarily focus on sensitising the learners to find and explore design solutions rather than understanding the nature of the design problem or the user's needs and wants. If the assumption is made that the participants of Groups A and C had some prior knowledge of what the problem entailed, it can be expected that they would have focused more dominantly on the primary instruction, which is to 'find a solution'.

When qualitatively analysing the cognitive phases, it is important to keep in mind that the problem structuring and problem solving cognitive phases may overlap, and that it is not always clear where problem structuring ends or problem solving starts or ends (Goel, 1995; Restrepo & Christiaans, 2004) (refer to my discussions in Chapter 2). As a broad indication, in the current study, problem structuring events were characterised by the processes involved in participants reading a design problem instructions; asking each other questions about the constraints and requirements; looking for information and acquiring knowledge about the elements in the design problem space; attempted to gain clarity about the design intention for the structure, behaviour and function of the artefact in terms of the specific need; and evaluated their own understanding of the design problem. An example of the problem structuring events that occurred for the different groups of participants is captured in Excerpts 4.1 to 4.3.

P1: (Reading from the instructions) Right, so what is the problem, the problem that should be solved and how should we solve it?

P2: So the problem is that we need to design a food container out of recyclable material that can hold the pap and the meat.

P1: But what about the heat conductor?

P3: Not a conductor, but an insulator.

Excerpt 4.1: Problem structuring events of Group A

P3: (Reading from the instructions) So, start with the first question. What is the problem or problems that needs to be solved and how can we solve it?

P2: The food that they are selling, the container must not be a conductor of heat. The packaging must not let the food get colder.

Excerpt 4.2: Problem structuring events of Group B

P2: You see the problem is, is that you can be able to recycle something like plastic. It's not necessarily biodegradable, but the problem is that it doesn't clean easily – the polystyrene.

P1: Ja, especially with the gravy.

P2: So, you need something that can be cleaned easily.

Excerpt 4.3: Problem structuring events of Group C

From these accounts, I was able to identify the participants' problem structuring events when they read the instructions from the problem statement, which requiring of them to identify the design problem. However, some participants also seemingly engaged in problem structuring events without even reading from the design brief, as demonstrated in Excerpt 4.3. In this case, Group C's participants engaged in problem structuring only later, after analysing the features of an existing product and searching for suitable materials for their design solution.

As in the case of the problem structuring events that could be identified, I noted some instances where the participants engaged in problem solving cognitive phases. These examples are captured in Excerpts 4.4 to 4.6.

P2: A ball can actually work

P3: It will be difficult to make a ball

P2: No, it will not be. Let me show you. You take this ball and then you put..

P1: Do we have to buy a ball?

P2: No, you can make a cardboard ball. It will be difficult to make the ball, but you can put the food in there. You just need to pack the food in tightly so that it can be sturdy, and then you can use wood to keep it sturdy.

Excerpt 4.4: Problem solving phase by Group A

P3: Ok, like since I started like the thing of foil for the packaging, why don't we start with foil

P1: And on the outside we can have like something that does not conduct the heat so it will not burn a person. We can have a tinfoil box inside and we can have a polyester box on the outside.

Excerpt 4.5: Problem solving phase by Group B

P1: I think the air can work. We just need to find a way to fill it in. Cause if we have like layers, one layer here and one layer there (pointing to Figure 6).

P3: Yes, like here (pointing to own drawing), I left out the space where we can put in something like air to keep it warm.

P1: When people squash it, it doesn't have to be completely made out of air. Cause, if you have little holes on the inside, then the air won't come out. It will just move around in there.

Excerpt 4.6: Problem solving phase by Group C

These excerpts demonstrate how some problem solving events occurred when the participants conceptualised possible functions, behaviour or the structures of envisioned design solutions during talking, writing, drawing or 3D modelling events, and when they developed and evaluated their proposed solutions. In addition, the participants of Groups A and C demonstrated leaky phases which contained a combination of elements of problem structuring and problem solving cognitive phases, as demonstrated by Excerpts 4.7 and 4.8.

P2: We can perhaps do something like a food bag, then you put something inside that can divide it in half.

P1: Or we can perhaps insert a box in the bag… But is this not a bit too expensive for someone next to the street?

P2: Yes, well that is why we will not be making a textile bag, but a wood or a cardboard one. Then we can just put foil inside, and then it has two materials that can take the hits

Excerpt 4.7: Leaky phase by Group A

P3: Um, what about like a rubber box? And then like a paper towel with something to put on your food.

P1: An you can use that again. You can just wash it. But then will mostly be for like, people who are eating there. Cause you can't wash a rubber thing when people go with it.

P2: I am just thinking it is going to cost a lot.

Excerpt 4.8: Leaky phase by Group C

As indicated by Excerpts 4.7 and 4.8, leaky phases occurred when the participants engaged in the design problem solving phase, while simultaneously deciding to structure the design problem. In both these excerpts, the groups of participants were engaged in generating solutions to the design problem when they realised that they had to design solutions that would be suitable for the design context in terms of the cost of the food container. As such, I was able to identify each group of participants' leaky phases when they generated utterances that indicated idea generation and development while simultaneously producing utterances of understanding or finding missing information about the people involved, the design objectives, the problem context or of the knowledge required to address the design problem.

This finding that leaky phases will occur throughout the process of structuring and solving design problems is supported by existing literature in the field of design cognition. For example, Dorst and Cross (2001), Goel (1995) as well as Cash and Gonçalves (2017) emphasise the necessary requirement of leaky phases for effective design problem solving to occur. As I did not obtain congruent findings across the three groups, the question as to whether or not learners will solve design problems in the way that novice designers or expert designers do in terms of the occurrences of leaky phases. This finding thus requires ongoing research. It needs to be kept in mind that various factors may however affect the process and enactment of leaky phases such as context, problem type, prior knowledge and experience, as well as available resources.

4.2.3 Types of design moves

In the linkographs that were generated (Figures 4.1 to 4.3), each group of participants generated different types of design moves. An overview of these is provided in Table 4.2.

Table 4.2: Number of different types of design moves per group

	Orphan moves	Unidirectional forward moves	Unidirectional backward moves	Bidirectional moves	Total number of design moves
Group A	2	19	88	284	393
Group B	0	22	55	80	160
Group C	1	18	54	158	231

4.2.3.1 Orphan moves

According to the data, all of the groups generated less than three orphan moves each, which indicates that in each group only a limited number of design moves did not link backward or forward to other design moves. This implies that the participants were able to coherently connect their emerging thoughts to previous design moves, thereby confirming the work of Gero and Kan (2017) as well as Goldschmidt (2014), who indicate that expert designers will synthesise their design ideas by means of connected thought processes rather than relying on random occurring thoughts.

Examples of the few orphan moves I identified are included in Excerpts 4.9 and 4.10.

P2: I wonder if we can’t perhaps design and make our own material where we combine plastic and cardboard?

Excerpt 4.9: Orphan move by Group A

P2: I was thinking that at every stop, there is a special like box where you can throw in your container. So when you get home

Excerpt 4.10: Orphan move by Group C

In both cases, some of the participants made suggestions during the problem solving cognitive phase. However, these suggestions did not receive responses from their team members neither were they referred to again as the design processes continued. As a result, these design moves were indicated as orphan moves in the linkograph. In this regard, Goldschmidt (2014) notes that limited numbers of orphan moves can be found in many linkographs, however this is more likely in the case of designers being novices rather than experts. A possible reason for this is that experts are generally able to anticipate the implications of their moves for longer stretches of future probable moves (Goldschmidt, 2014).

The finding that the learners in the current study, who can be considered as naïve or novice designers, only produced three orphan moves in total, therefore seemingly contradict Goldschmidt's (2014) research. Merely taking Goldschmidt's (2014) work as basic premise would imply that the participants in my study were potentially able to anticipate the implications of their design moves, however this does not seem probable in the case of novice designers. As such, ongoing research in this area is required in order to explain this finding. Even though the apparent contradictory finding may perhaps be ascribed to factors such as the participants' prior knowledge of the materials, or a similar design task in their technology education, these are mere working assumptions that merits further investigation.

4.2.3.2 Unidirectional forward and backward moves

When looking at the number of unidirectional moves that were generated, the participants in all three groups produced more unidirectional backward design moves, when compared to their unidirectional forward moves. In linkography, unidirectional backward moves suggest that at the instant of their generation the participants were paying attention to what had transpired up to that point, rather than considering future implications or producing new thoughts (Goldschmidt, 2014). On the contrary, unidirectional forward moves would imply that participants generate new thoughts, without thinking about previously generated thoughts to which future design moves may link (Goldschmidt, 2014). I include examples of unidirectional forward moves that emerged during designing in Excerpts 4.11 to 4.13, with examples of unidirectional backward moves following my discussion of the forward moves.

P2: What if we make the container in a triangular format? A triangle is the strongest shape.

Excerpt 4.11: Unidirectional forward move of Group A

P2: How will the food container be used?

Excerpt 4.12: Unidirectional forward move of Group B

P1: What about rubber?

Excerpt 4.13: Unidirectional forward move of Group C

The qualitative data that are captured in Excerpts 4.11 to 4.13 indicate the generation of unidirectional forward moves during the first 20 minutes of each group of participants' process of design problem solving. In Excerpt 4.11, P2 in Group A for example generated a unidirectional forward move when he proposed a shape for their design solution based on his previous knowledge about the strength of triangular shaped structures. Prior to the instantiation of this design move, no mention was however made of a suitable shape for their design solution. In a different scenario, Group B generated a unidirectional forward move when P2 started reading from the problem statement instructions (Excerpt 4.12). By reading the guidelines related to how the food container would be used, P2 was able to generate a unidirectional forward move to which future design moves could link back in terms of how the people involved would be using the food container.

Finally, in Excerpt 4.13, P1 in Group C attempted to identify a material that would be recyclable and biodegradable, from which the food container could potentially be made. After evaluating and rejecting materials made from metal, P1 proceeded to generate a unidirectional forward move when suggesting rubber. Next, examples of unidirectional backward moves from Groups A to C are captured in Excerpts 4.14 to 4.16.

P1: So, we will be using foil. Write down foil.

Excerpt 4.14: Unidirectional backward move of Group A

P3: The food container should then be recyclable and it should be an insulator of heat.

Excerpt 4.15: Unidirectional backward move of Group B

P2: I'm just thinking, it is going to cost a lot.

Excerpt 4.16: Unidirectional backward move of Group C

These excerpts illustrate how each group generated unidirectional backward design moves. In Excerpt 4.14, P1 in Group A, for example, generated a unidirectional backward design move when P1 was summarising their groups' decision to use aluminium foil as a recyclable material from which their food container could be made (Excerpt, 4.14). For Group B, P3 in Group B was apparently considering the instructions of the problem statement when thinking of a prior instance when the group mentioned that the material had to be recyclable and an insulator of heat (Excerpt 4.15). Finally, in Excerpt 4.16, Group C generated a unidirectional backward move when P2 evaluated P1's proposal of using a rubber box as a food container due to rubber being an expensive material. In summary, Figures 4.5 to 4.7, provide overviews of the distribution of the unidirectional moves for the various groups of participants.

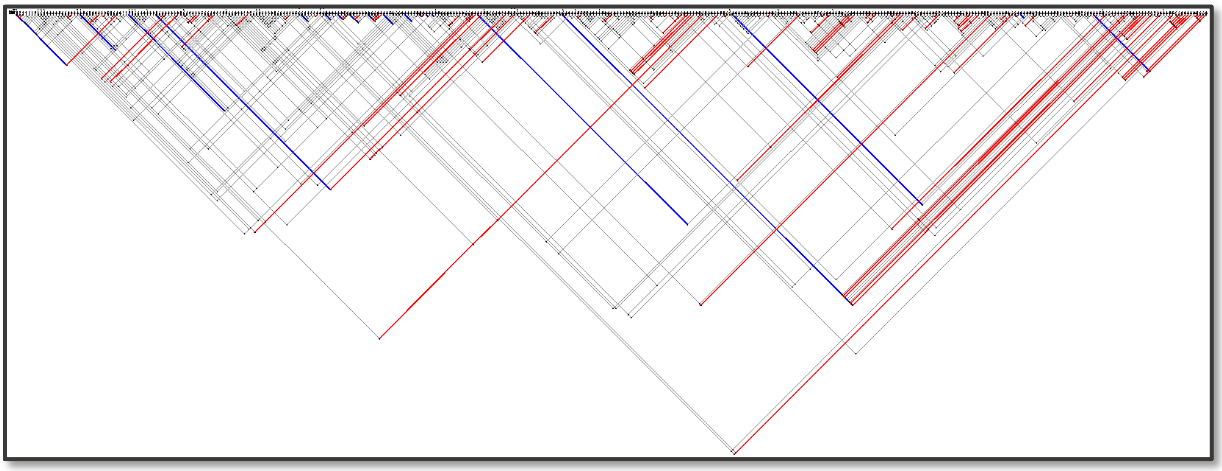


Figure 4.5: Distribution of unidirectional forward (blue) and backward (red) design moves of Group A

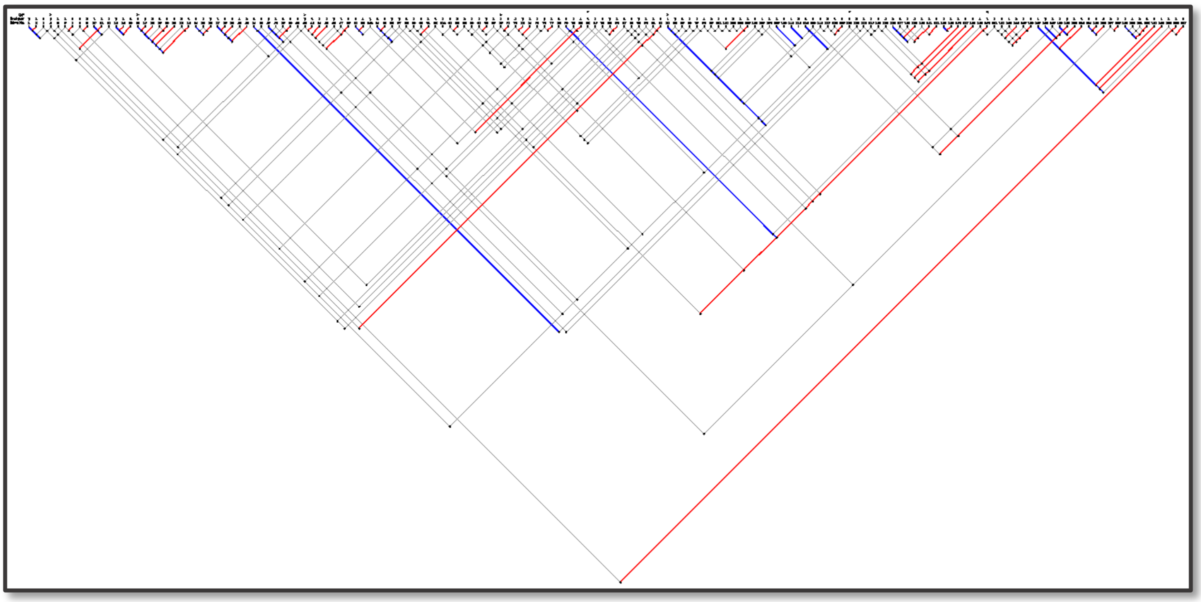


Figure 4.6: Distribution of unidirectional forward (blue) and backward (red) design moves of Group B

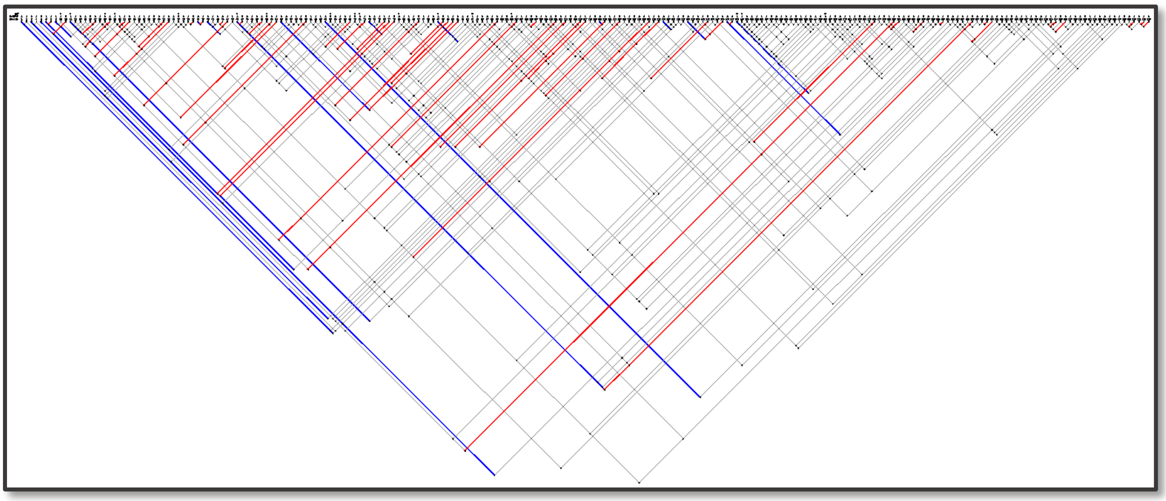


Figure 4.7: Distribution of unidirectional forward (blue) and backward (red) design moves of Group C

When reviewing the distribution of the unidirectional backward and forward moves, as captured in Figures 4.5 to 4.7, it can be seen that, for each group of participants the unidirectional moves are distributed across the sequence of design moves, instead of being concentrated at, for example, the beginning or end of the design process. According to Goldschmidt (2014), this result suggests that the sequence of design moves of the participants were well integrated, implying that the participants were able to continuously link new emerging thoughts with subsequent design moves, thereby resembling the typical behaviour of expert designers. In this way, the findings of my study provide some evidence that Goldschmidt's (2014) research with expert designers may be applicable in the case of novice designers too. This possibility furthermore highlights the importance for ongoing research, in order to confirm or reject such a possibility.

4.2.3.3 Bidirectional design moves

In terms of the bidirectional moves, the quantitative analysis as captured in Table 4.2, indicates that for each group of participants, between 50% and 72% of the total number of design moves were bidirectional. This finding supports Goldschmidt's (2014) work, which indicates that a proportion of bidirectional moves, close to two-thirds, is typical of novice professional designers. While Groups A and C are close to the indicated percentage of two thirds of the total design moves, Group B only produced 50% (80 out of 160) bidirectional moves. One explanation for Group B's lower percentage of bidirectional moves may potentially be linked to their limited engagement in the problem solving cognitive phases, as discussed in Section, 4.2.2, with the indicated possible underlying reasons being applicable in this instance too.

This finding however warrants further investigation, specifically in terms of the debate on whether or not "novice designers are not capable of switching their modes of thinking between convergent and divergent thinking as frequently as practising designers" (Wong & Siu, 2012, p. 447). Although previous research (Howard-Jones, 2002; Pringle & Snowden, 2017; Wong & Siu, 2012) has echoed the importance of concurrent generative and evaluative thoughts, which is demonstrated in bidirectional thoughts during designing, few studies have empirically investigated when or how these thoughts will typically occur (Goldschmidt, 2016). Current methods analysing the shifts between generative and evaluative thinking processes tend to focus only on generative, divergent processes, but neglect the dynamic nature of concurrent convergent and evaluative processes (Goldschmidt, 2016; Sowden, Pringle & Gabora, 2015; Wong & Siu, 2012). These variations in findings and trends point to the importance of ongoing research on designers' integration of backward and forward moves in solving design problems, by applying bidirectional moves.

Qualitative supportive evidence for the bidirectional design moves generated by Groups A to C is captured in Excerpts 4.17 to 4.19.

P3: Let's search for one more idea. Maybe something like this (Pointing to Figure 14)? This is like that circle shape you spoke about earlier.

Excerpt 4.17: Bidirectional move by Group A

P2: Yes, the materials should be recyclable, but they should also not be too heavy, because they said there will be food in there.

Excerpt 4.18: Bidirectional move by Group B

P1: We cannot use any metal. That's a lot of money (pointing to aluminium foil container). Black people probably would not use it because they have the cheapest source already

Excerpt 4.19: Bidirectional move by Group C

From these excerpts it seems clear that the different groups generated bidirectional design moves in different ways. Group A generated a bidirectional design move when P3 was finding a suitable solution to the design problem. While gazing at Figure 14, in the STEM task, he generated a forward link by proposing an octagonal cylinder as possible shape for the container, but also recalled an earlier instance where P2 proposed a ball shaped container, thereby creating a backlink. In Excerpt 4.18, P2 in Group B generated a design idea when she repeated a statement on the material for the container having to be recyclable (backlink) while creating a forelink by adding that the material should not be too heavy. Finally, P1 in Group C generated a forward link when he proposed the use of metal as material to make the container, but at the same time generated a backlink when he evaluated its suitability, in terms of the cost of the material and linking this to the context in which the food container would be used.

More specifically, a focus on learner and novice designers is required. In Chapter 5, I elaborate on the results pertaining to the information sources that underlay the nature of the bidirectional thoughts of the participants in the current study.

4.2.3.4 Critical moves

The participants generated several critical moves during their design processes. For my study, each group of participants had a different threshold, according to the guideline of Goldschmidt (2014), to identify the 10-12% moves with the highest links of the total number of moves. The threshold identified will determine the number of links required to signify a critical move. For the current study, the number of critical moves generated per threshold for the various groups, and the balance between critical forward moves (CM>) and critical backward moves (<CM) are captured in Table 4.3.

Table 4.3: Ratio of critical moves between the groups

	Threshold	Number of CMs	%CM>	%CM<
Group A	CM^8	31	84	16
Group B	CM^6	18	72	28
Group C	CM^7	25	88	12

The data in Table 4.3 indicate that the various groups of participants generated different numbers of critical moves, based on the identified thresholds. When looking at the ratio of <CM to CM>, it is close to 80:20 for Groups A and C; and 70:30 for Group B. According to Goldschmidt (2016), this ratio is usually 60:40 in the case of professional designers. As such, the finding of the current study indicates a higher ratio than what can be expected from professional designers. This implies that the participants in my study were able to generate new emerging thoughts that were critical for the development of future design moves, however were unable to generate thoughts that were critical in developing, exploring or summarising previously generated thoughts. When taking into account that Goldschmidt's (2016) research primarily focuses on professional designers, and based on the fact that my study involved learners who can be regarded as novice designers, the discrepancy between what I found and what is known may potentially be ascribed to the limited available literature in the field. More specifically, pedagogical guidelines for fostering reflective and evaluative thinking during designing is scarce, as is the literature base on procedural fluency in terms of evaluative and reflective thinking (Goldschmidt, 2016; Pringle & Snowden, 2017; Sowden et al., 2015). It follows that no final conclusions can be made without further research in the field.

On a broader generic level, the findings of this study support existing research on design education in both professional and school contexts, which provides evidence that novice designers may engage in generative thinking at the expense of evaluative thinking (Mentzer, 2014; Stempfle & Badke-Schaub, 2002; Welch, 1996). This further implies that evaluative and reflective thinking is a skill that needs to be taught intentionally. Although strategies for teaching evaluative thinking have recently emerged in professional design literature (Pringle & Snowden, 2017; Sowden et al., 2015), a paucity of research remains in terms of the nature of such reflective and evaluative thinking processes (Goldschmidt, 2016), which requires ongoing research.

With regard to the emergence and distribution of the critical backward and critical forward moves, the linkographs captured in Figures 4.8 to 4.10 demonstrate the various groups of participants' design processes.

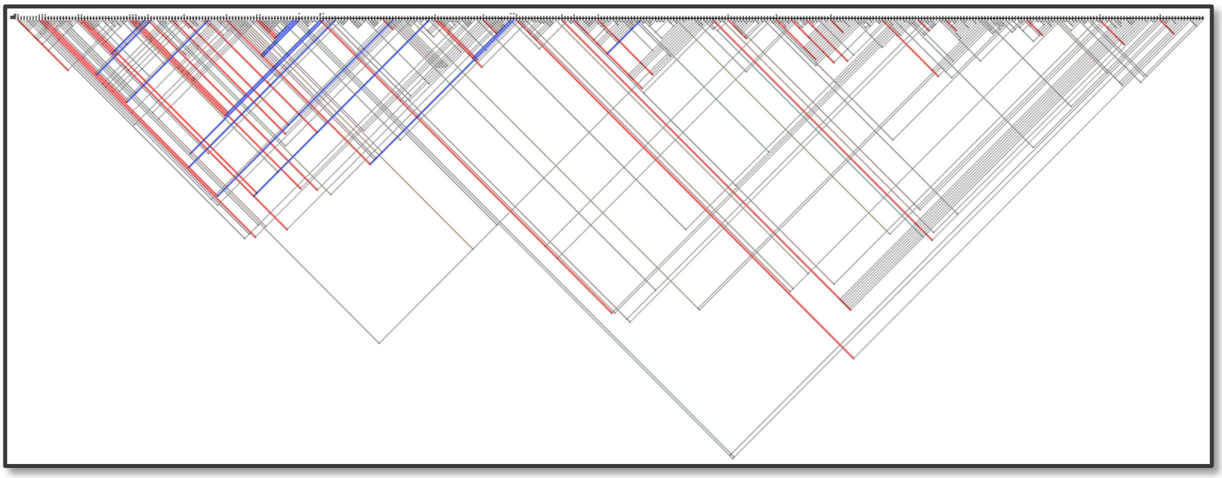


Figure 4.8: Critical forward moves (red) and critical backward moves (blue) of Group A

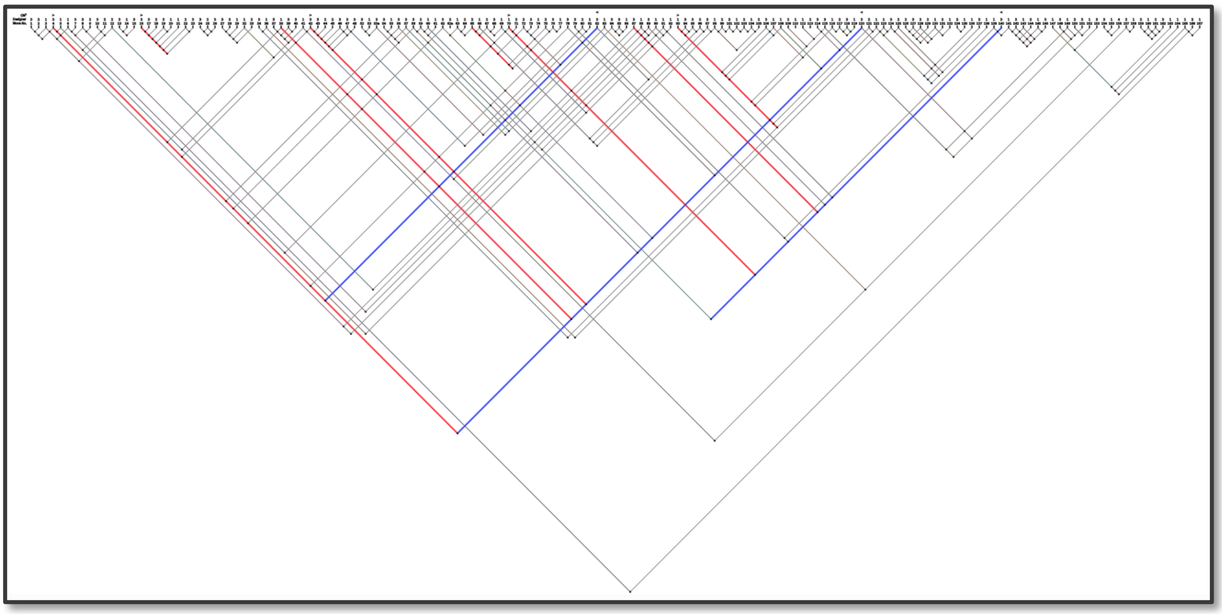


Figure 4.9: Critical forward moves (red) and critical backward moves (blue) of Group B

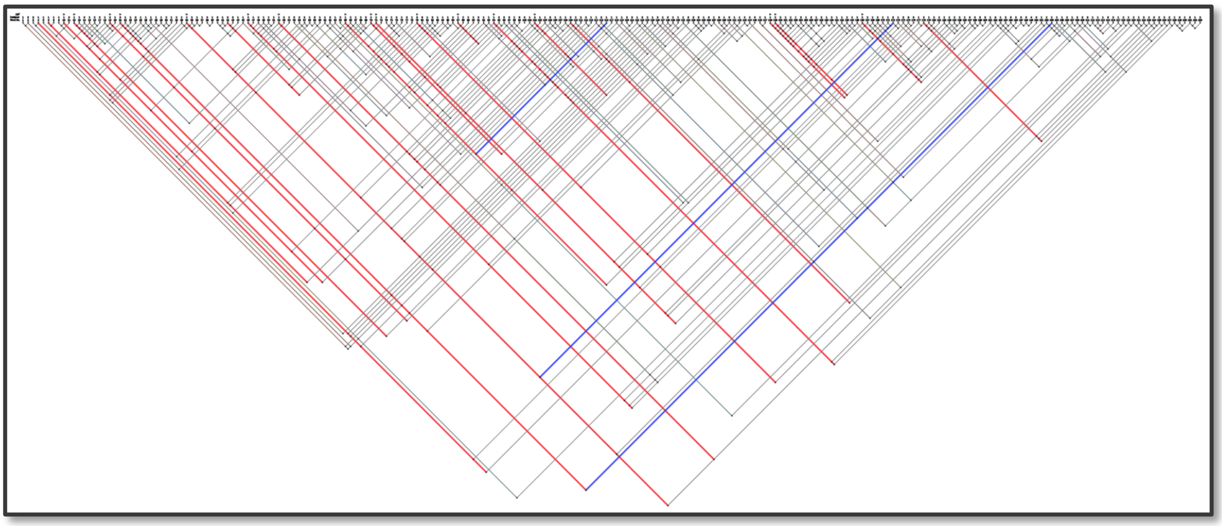


Figure 4.10: Critical forward moves (red) and critical backward moves (blue) of Group C

Figures 4.8 to 4.10 illustrate the frequency of the emerging critical moves of the groups of participants, and support the data captured in Table 4.3, by highlighting the limited critical backward design (blue) moves that were generated. From all the groups, Group A generated the most critical backward design moves when compared to Groups B and C, who each only generated three critical backward design moves. This difference may possibly be accounted for in terms of factors such as prior training in evaluative thinking strategies, or certain participants exhibiting strong leadership roles in taking stock of available design ideas in order to plan future design moves. However, these remain speculative assumptions and require further research.

Furthermore, the data in Figures 4.8 to 4.10 indicate the distribution of the critical moves within each of the group's design processes. In Figure 4.8, Group A's linkograph, for example highlights the finding that the majority of the critical backward moves were generated in the first half of the design process, indicating that the participants made critical decisions early in the design process, but did not necessarily engage in evaluative or reflective thoughts during the second half of the process. This implies that Group A thus made the most significant design decisions during the first half of their design process, after which they implemented their plans with limited significant reflective thoughts occurring during the second half of the design process.

On the contrary, Figures 4.9 and 4.10 indicate that Groups B and C generated most of their critical backward design moves toward the middle and end of the design process, but due to the limited number of design moves, did not engage in sufficient reflective and evaluative processes. A possible reason for this finding may relate to the limited pedagogical support in the learning environment or insufficient available instructional materials and resources that may provide scaffolds to learners to engage in reflective and evaluative thinking. Qualitative supportive evidence for the critical design moves generated by Groups A to C are included in Excerpts 4.20 to 4.22, which I discuss as they occurred moment-to-moment, when the critical moves emerged as the designing progressed.

P1: (Move 55) The insulation material... Which one is biodegradable?

P3: (Move 56) Yes, that is the problem

P2: (Move 57) Foil?

P3: (Move 58) I don't think foil is?

P2: (Move 59) We need to get something halfway?

P1: (Move 60) Well, it does not say here (looks to teacher for help)

T: (Move 61) Foil is recyclable

P2: (Move 62) Alright, so foil can work!

P1: (Move 65) So we will be using foil? Write foil down

Excerpt 4.20: Critical design move by Group A

After coding each of the utterances in the verbal protocol, I identified design move 55 (refer to Excerpt 4.20, bold green font) as a critical forward design move based on the threshold of 8 or more links to succeeding design moves (orange font). Prior to the instantiation of move 55, the participants were engaged in a problem solving cognitive phase, trying to find suitable insulation materials, when P1 proceeded into a problem structuring cognitive phase by asking which of the discussed insulation materials are biodegradable. This shift of attention to biodegradable design intention seemingly refocused the team members and resulted in them recalling information about biodegradable material properties. As a result, P3 seemingly realised that the team had only been discussing unbiodegradable materials for their food packaging up to that point, while P2 asked whether or not aluminium foil might be a biodegradable insulating material. The participants' uncertainty about the material properties was apparently seemed to be resolved when, during design move 60, P1 asked the teacher's assistance by stating that the notes did not contain the necessary information for them to make a design decision. This resulted in the teacher disclosing that aluminium foil is recyclable, in turn leading to the participants discarding their biodegradable design intention and only pay attention to recyclable materials onwards. As a result, participants decided to used aluminium foil in their final design.

The incremental emergence of the design moves, starting at move 55, is evident of the participants' generation of a critical move during a problem structuring cognitive event. This critical move was significant for Group A as this marked the point where they stopped paying attention to biodegradable materials and started focusing on recyclable materials instead, as revealed in Figure 4.11.

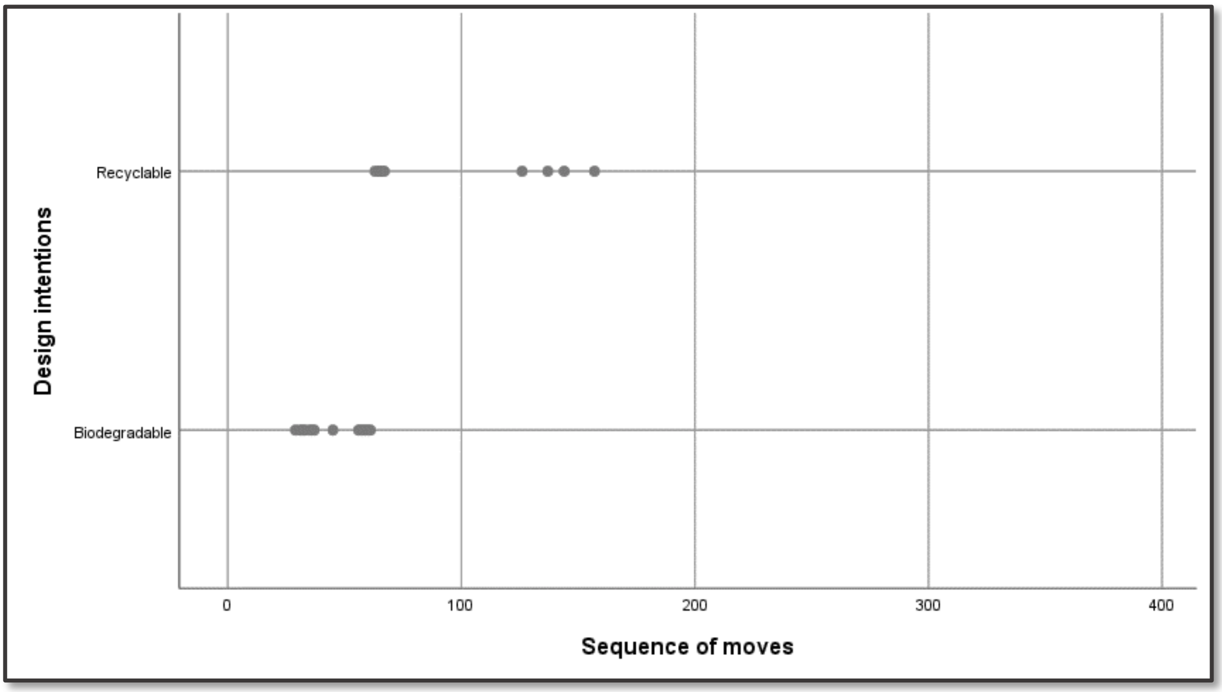


Figure 4.11: Attention to biodegradability and recyclability design intentions (Group A)

In interpreting Figure 4.11, the instances where participants in Group A mentioned their design intentions thus indicate that the participants shifted their attention from a biodegradability design intention to a recyclability design intention as the process progressed. This shift of attention was seemingly supported by the emergence of move 55, which I identified as a critical forward design move, as discussed earlier.

Group B's critical backward design move is captured in Excerpt 4.21, as illustrated during a problem solving cognitive phase event is illustrated.

P3: (Move 4) Ok, like since I started like the thing of the foil for the packaging, why don't we start it with foil?

P1: (Move 42) It should have like a handle. It's going to be hot to carry the foil

P3: (Move 58) So we are going to be using tinfoil. The packaging will have tin foil.

P1: (Move 108) It should be a colour that absorbs heat, like black.

P2: (Move 109) Or we put this (pointing to cardboard) on the inside, and then we put black (Pointing to black foam paper) on the outside

P3: (Move 115) So in the specifications, we will be using black foam paper.

P2: (Move 120) Hmmm, so two things that we need to include. Colours black. Should be made out of foam paper and what else? Tinfoil?

Excerpt 4.21: Critical backward move by Group B

This critical backward move (move 120, bold green font) was identified based on the threshold of 6 or more links to preceding design moves (shown in orange font). Move 120 in the sequence of the other design moves, summarises the thoughts that occurred during the design process which seemingly resulted in a design choice by the group. From the beginning of the design process, P3 started generating a design idea which could potentially utilise aluminium foil as material. This thought was repeated in moves 42 and 58. Later in their design process, when deciding on how the food packaging should look like, P1 suggested the use of black as colour for the food container, as it would absorb heat. Subsequently, P2 gazed and pointed to the cardboard and black foam paper as materials that could be used to make the food container, which was repeated in move 115. Finally, a critical backward design move emerged when P2 summarised their design choice to use black foam paper and aluminium foil to manufacture their food container.

In Excerpt 4.22, the final example of a critical forward design move during a problem solving cognitive phase is demonstrated – in this case for Group C.

P1: (Move 34) How about we do one made out of cardboard for the pap, and then another container for the gravy?

P2: (Move 35): At least one that maybe a cardboard outside and a plastic lining on the inside.

P1: (Move 36) Maybe for the gravy something like this (Points to Figure 10)?

P1: (Move 52) Possibly it has to be a two piece thing

P2: (Move 53) Mmmm, the gravy and the pap needs to be sold separately.

P2: (Move 102) Try and make two separate compartments for the pap and the gravy

P1: (Move 114) Cause we can still make another container for the gravy. Like a smaller cylinder that goes in there.

P2: (Move 125) Ja, but see, the problem with cardboard is it can get soggy and if it is laminated its not recyclable or biodegradable anymore.

Excerpt 4.22: Critical forward design move by Group C

Group C thus generated a critical forward move during a problem solving cognitive event during move 34 (bold green font). This move (move 34) was identified based on the threshold of 7 or more links to succeeding design moves (orange font). Early in the design process executed by Group C, during move 34, P1 introduced their design intention to design a food container that would separate the pap and the gravy for consumers in two separate containers (move 34). In move 35, P2 added that the containers had to be made from different materials, which led P1 to point to and identify Figure 10 in the design brief as a possible solution element. During later stages, at moves 52, 53, 102 and 114 both P1 and P2 reiterated that their design solution had to consist of separate containers for the pap and the gravy, and repeated the thought of a cylindrical shaped container for the gravy, as indicated in Figure 10 of the STEM task. Finally, P2 evaluated the use of cardboard for the gravy, based on his understanding of the properties of materials, and the possible use of lamination to prevent deformation when catering for wet substances.

In summary, Excerpts 4.20 to 4.22 illustrate how each group of participants were able to generate critical design moves that provided an indication of their intentions during their processes of designing. This finding aligns with the work of various scholars in the field (refer to Coles & Norman, 2005; Trimingham, 2008; Young, 2004) who note that, what learners pay attention to during problem solving, is dependent on their design intentions. This finding furthermore relates to current trends in classroom practice where teachers often typically structure the physical learning environment according to learners' intentions and goals for problem solving (Barab & Roth, 2006; Young, 2004). In the next section, I discuss the results pertaining to the way in which the participants' interactions with social structures influenced their processes of designing.

4.3 INTERACTIONS WITH SOCIAL STRUCTURES

In this section, I foreground the ways in which the individual members of each group of participants interacted with each other during the STEM tasks. As an overview, Figure 4.12 provides a summary of the contributions of individual group members to the generation of design moves.

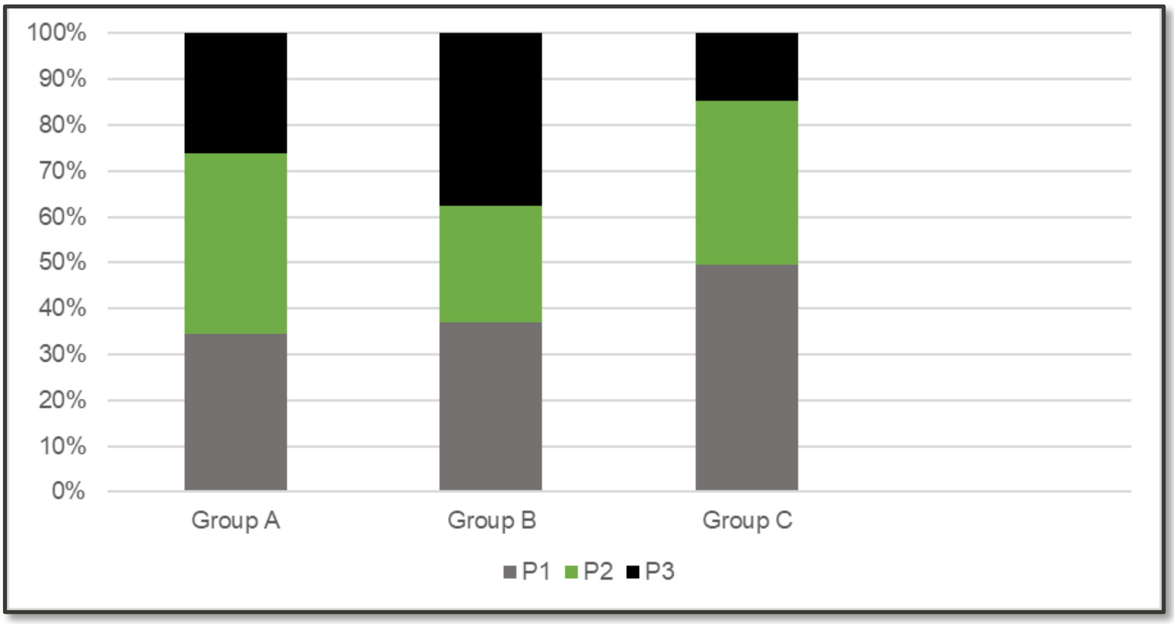


Figure 4.12: Individual contributions by members of Groups A to C

Figure 4.12 indicates that, for Group A, P2 generated the most design moves (39%), with P1 generating 34% of the total of their design moves and P3 the least (26%). In Group B, P1 and P3 generated almost the same number of design moves (37% and

38% respectively), while P2 generated the least (25%). In Group C, P1 generated 50% of the total number of design moves, with P2 generating 35%, and P3 generating the least (14%). These results point to the tendency of one participant always generating fewer design moves than the rest of the design team when participating in collaborative designing.

The results I obtained in this regard can be linked to my conceptual framework, that emphasises the social nature of designing. Based on my integration of Extended Design Cognition (Haupt, 2015) and Activity Systems Theories (Engeström, 2015), I regard social interactions as a significant tool for thinking (Vygotsky, 1987), which explains the finding that a design team's effectiveness in solving design problems will depend on the abilities of the group members to access and use their individual contributions during the design process. In this way, cognition has been viewed to not only develop as a result of language (Vygotsky, 1987), but can also extend the capabilities of team members (Carter, Clark, Kallestrup, Palermos, & Pritchard, 2018) as a result of social interaction. More specifically, socially extended cognition implies that cognitive processes are constituted by social interactions that collectively realise epistemic states such as knowledge and beliefs (Carter et al., 2018). However, further research is required to characterise team design processes through the lens of socially extended cognition.

In order to gain a deeper understanding of the nature of the contribution of each participant made in terms of the generated design moves, I also analysed the link index of each participant, as well as the number and types of design moves that each individual participant generated in light of the number of design moves they generated during designing, as captured in Table 4.4.

Table 4.4: Number of the types of design moves per participant

		Link index	Unidirectional moves	Bidirectional moves
Group A	P1	2	38	95
	P2	2.9	35	119
	P3	1.71	34	69
Group B	P1	1.5	26	32
	P2	1.1	18	20
	P3	1.9	32	28
Group C	P1	2.4	35	79
	P2	2.4	24	57
	P3	1.6	12	22

The productivity of each group member is not only indicated by the number of design moves generated, as indicated in Figure 4.8 (refer back to Section 4.2.3.3), but also by the link index, as captured in Table 4.4. In Group A, P2 seemed to be the most productive team member, producing almost three links per generated design move, while P3 produced less than two links per design move. In Group B, P3 was the most productive group member, generating an average of 1.9 links per design move, while P2 only generated 1.1 links on average. Finally, in Group C, P1 and P2 were the most productive group members, producing an average of 2.4 links per design move, with P3 merely producing 1.6 links. Overall, the individuals in Group B thus seemed less productive than those in the other two groups.

To further understand the team dynamics between individual participants, I investigated each participant's contribution in terms of the critical moves they generated and the proportion between <CM and CM>, as captured in Table 4.5.

Table 4.5: Percentage of critical moves contributed by individual participants

Group A		#CM^{8}	% <CM^{8}	% CM^{8}>
	P1	11	73	27
	P2	17	94	6
	P3	3	66	33
	Total	31	84	16
Group B		**#CM^{6}**	**% <CM^{6}**	**% CM^{6}>**
	P1	7	86	14
	P2	2	100	0
	P3	9	56	44
	Total	18	72	28
Group C		#CM^{7}	% <CM^{7}	% CM^{7}>
	P1	12	83	17
	P2	11	91	9
	P3	2	100	0
	Total	25	88	12

At first glance, not all of the participants in each group seemed equally productive. In each of the groups, the team generated different numbers of critical moves. As indicated earlier in Group A, P1 and P2 generated the most design moves, yet also generated significantly more critical moves than P3. When looking at the proportion of generated <CM in relation to CM>, on the one hand, P2 provided an example of a designer who is better at generating design moves that propose new ideas (forelinks) than generating design moves that summarise or develop previously instantiated design ideas (backlinks). P1 and P3, on the other hand, demonstrated the ability to generate both <CM and CM>.

In Group B, P1 and P3 generated the most critical moves (seven and nine respectively), with P2 only generating two critical moves. Both P1 and P3 were able to generate both <CM and CM>, whereas P2 generated only CM>. Finally, in Group C, P1 and P2 seemed to be the most productive team members, who generated 11 and 12 critical moves respectively. When looking at the proportion of <CM and CM>, P1 and P2 primarily generated CM>.

The proportion between <CM and CM> of each group of participants, as depicted in Table 4.5, reveals that some of the participants generated a high proportion CM> compared to <CM. This implies that, during their social interactions, some participants

were seemingly less inclined to look back at what had transpired during the design process in order to generate new thoughts or to declare and repeat a design choice. It seems as though the participants with a high number of CM> were more preoccupied with raising new ideas and questions, which was also reflected in the high proportion of CM>. One participant, namely P2 in Group B, generated the highest percentage of <CM, which implies that he was able to summarise, repeat or finalise design choices in the group.

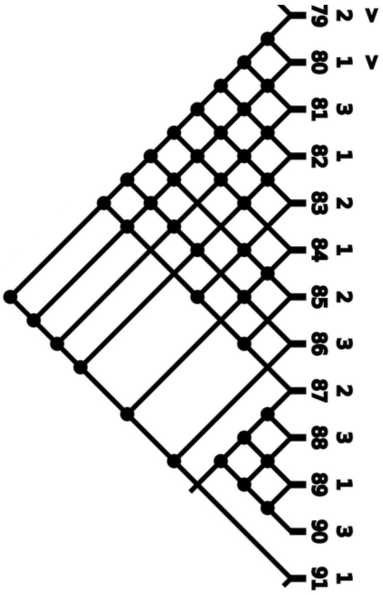
In order to understand the nature of the social interactions that occurred, I furthermore analysed the links related to the intrapersonal and interpersonal communication that transpired during the protocol (Jiang & Gero, 2017), as indicated in Table 4.6.

.**Table 4.6:** Intrapersonal and interpersonal links for the various groups

		Intrapersonal # links	**% links**	**Interpersonal # links**	**% links**
Group A	P1	95	35	180	65
	P2	172	39	267	61
	P3	48	27	129	73
	Teacher	0	0	3	100
	Total	**315**	**35**	**579**	**65**
Group B	P1	34	38	55	62
	P2	10	22	35	78
	P3	57	50	56	50
	Teacher	0	0	0	0
	Total	**101**	**41**	**146**	**59**
Group C	P1	161	59	112	41
	P2	86	44	111	56
	P3	16	28	41	72
	Teacher	0	0	0	0
	Total	**263**	**50**	**264**	**50**

The data in Table 4.6 indicate that Groups A and B generated the majority of the links from each other's design moves, thereby implying a high percentage of interpersonal communication, while Group C maintained a balance between generated interpersonal and intrapersonal links. Group A and B's high percentage of interpersonal links indicates that the participants relied on each other's design moves, which in turn resulted in interchanges of ideas and opinions during collaborative designing. In Group C, the balance between intrapersonal and interpersonal links indicates that the participants were equally involved in collaborative and individual designing. In this way, the 50% intrapersonal links indicate less successful team efforts as each participant tended to concentrate on their own ideas instead of considering other participants' contributions.

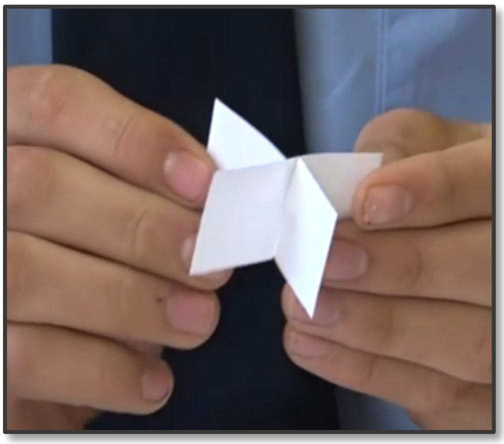
Excerpts 4.23 to 4.25 (which I separately discuss below) provide qualitative evidence for the social interactions that occurred between the participants in each group. Such interactions typically resulted in group members making design choice or more clearly understanding the problem context.



P2: (79) And then we can divide it in half or four compartments
P1: (80) But we can also make it so that it comes out
P3: (81) If you want to mix it?
P1: (82) So that, if you only have pap or, only meat then you can take it out
P2: (83) Then you can mix it. Then you only need a thing to hold on to when you take it out
P1: (84) (modelling the separator) look, when you cut it here, then you just take another paper and insert it there
P2: (85) So, don't you guys want to perhaps take two layers and put it into each other?
P3: (86) Then you just need a hole on the outside to keep the separator stable
P2: (87) I thought that we can add a string and then just pull it out. And then below you can add more food.
P3: (88) Oh, like two layers?
P1: (89) For what?
P3: (90) No, you really don't need two layers
P1: (91) Yes, so we agree (holding up model of separator)?

Excerpt 4.23: Social interaction in Group A (22:43)

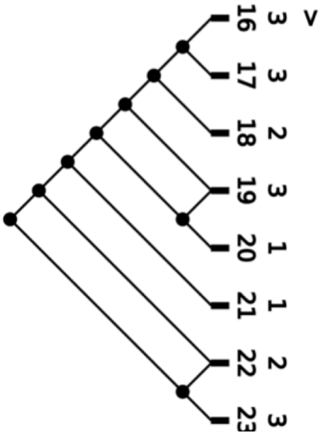
Excerpt 4.23 illustrates how the social interactions of P1, P2 and P3 in Group A resulted in them developing a physical partition to separate the pap (maize) from the meat and gravy. During design move 79, P2 generated a critical forward move when he reiterated a design intention to separate the pap from the meat and gravy. During design moves 80 to 83, P1, P2 and P3 interactively built on P2's design intention by proposing a partition that is removable. In justifying this idea, users' preference to combine the pap and the meat and gravy was predicted as possible advantage. These social interactions then led P1 to start 3D modelling the partition by using paper, based on the preceding design moves, as captured in Photograph 4.1.



Photograph 4.1: P1 making a 3D model during design move 84, based on design moves 79-82 (24:52)

After reviewing P1's 3D model, captured in moves 85 and 87, P2 proposed the use of a layered container where the pap and meat could be stored on top of each other. This proposal was, however, rejected during moves 88 to 90 when P1 and P3 questioned the use of a layered partition. Finally, P1 summarised and finalised the group's idea to use a modelled partition during design move 91 when he generated backlinks to the preceding design moves (79-86). In doing this, the various design moves that emerged as a result of the participants' social interactions gave rise to a physical embodiment of the initial design intention made in design move 79, and a design choice which was later used in the design process.

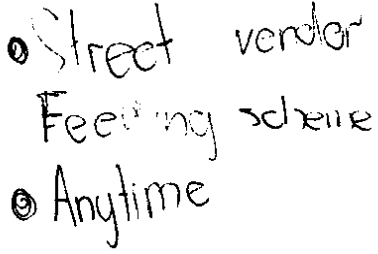
A different example of how the learners' social interactions led to their understanding of their design context is captured in Excerpt 4.24.



P3: (16) And where will the food container be used?
P3: (17) Anywhere?
P2: (18) Taxi rank corporations
P3: (19) Will be used at home, street vendors and the kitchen
P1: (20) We don't use it that much in the kitchen though
P1: (21) Inside the Taxi's
P2: (22) Maybe even at schools
P3: (23) Oh, you mean the feeding scheme and stuff?

Excerpt 4.24: Social interaction in Group B (14:55)

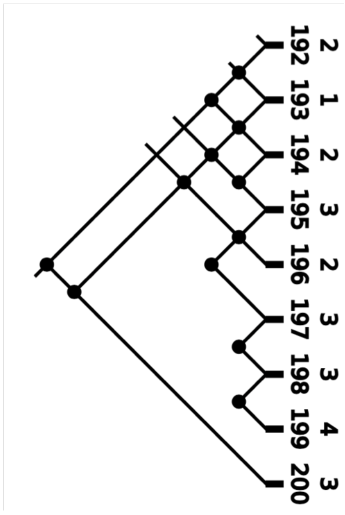
From Excerpt 4.24, it is evident that P3 generated a critical forward design move when he read "where will the food container be used?" from the problem statement instructions. As a result, the participants in Group B started to frame the problem context, generating backlinks when they suggested places where the food container could be used. As they generated backlinks, during move 19, P3 suggested that the food container may potentially be used in the home, which P1 evaluated, stating that they did not use takeaway food containers at home. P1 and P2 furthermore generated suitable places where the food container could be used, including places such in a taxi or at school. However, only street vendors, 'anywhere' and feeding schemes were written down by P3 as possible places of use by the participants, and did not include the proposals made by P1 and P2, as captured in Photograph 4.2.



- Street vendor
  Feeding scheme
- Anytime

Photograph 4.2: Problem context framing of where the food container will be used by Group B

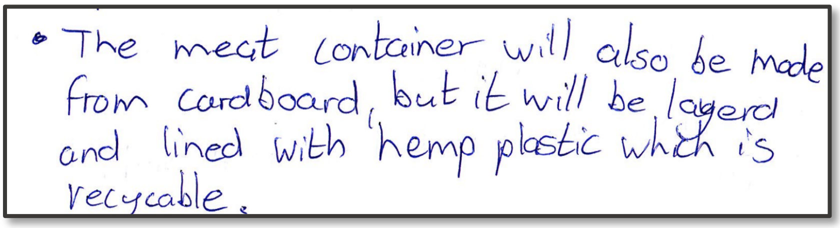
It follows that the social interactions between the various participants seemingly contributed to their problem framing when the participants spoke to each other. However, when P3 recorded the proposals in writing, he only documented his own proposals and not those of P1 and P2. In Excerpt 4.25, an example is provided of how Group C's social interactions led to a design choice to use hemp plastic as a suitable material for their design idea.



P2: (192) I was thinking, you remember when mam talked about hemp plastic… we can use that?
P1: (193) But isn't plastic hard to clean?
P2: (194) No, it's not that hard to clean, just wash it.
P3: (195) I read something here that it is hard to clean
P2: (196) Yes, but that is polystyrene
P3: (197) "Food vendors usually sell food to customers in plastic polystyrene containers. However, these containers do not retain the heat of the food inside the container for the trip home. Also, these containers are not easily recyclable because it is contaminated with food and difficult to clean because it is porous.
P3: (198) Sir, what does porous mean?
P4: (199) It means that it basically sucks in the food. So if you look at polystyrene there's small little holes where the food goes into
P3: (200) Ok, then it's not a big problem. We can just make it plastic.

Excerpt 4.25: Social interaction in Group C (51:22)

Prior to design move 192, the participants struggled to identify suitable materials that were both biodegradable and recyclable that could be used to manufacture their food container. During move 192, P2 however recalled an instance in one of their previous classes where the teacher had shown them Hemp plastic as an example of a biodegradable and recyclable alternative to conventional plastic. Nevertheless, this proposal was challenged by P1 and P3 in moves 193 and 195 when they recalled that the problem statement instructions mentioned that plastic is difficult to clean. However, P2 however maintained in move 196 that this was only relevant to polystyrene. Subsequently, P3 read the problem statement instructions again in order to verify P2's design move. In this way, the problem statement instructions served as an external memory device that P3 could use (Heersmink, 2015; Menary & Gillet, 2017). Upon reading the problem statement instruction, P3 was not sure what the term 'porous' meant and as a result asked the teacher for assistance during design move 198. By asking the teacher, P3 could realise that his previous idea that all plastic is hard to clean was incorrect, and subsequently made the design choice to use hemp plastic as a suitable material for their food container. This was confirmed when P1 made notes on their design brief during a later episode, as captured in Photograph 4.3.



- The meat container will also be made from cardboard, but it will be layerd and lined with hemp plastic which is recycable.

Photograph 4.3: Group C's design choice to use hemp plastic as a suitable material for the meat container (01:06:11)

Excerpt 4.25 and Photograph 4.3 therefore illustrate how social interactions resulted in the participants' design choice to use hemp plastic as a suitable material for their food container. While P2 generated the design move that proposed hemp plastic as a suitable material, both P1 and P3 were sceptical based on their understanding of the problem statement instructions and generated backlinks that were generated during moves 193 and 195 as well as during move 192 when they questioned whether or not plastic could be cleaned easily. However, once P3 revisited the problem statement instructions and asked their teacher for help in order to understand the term 'porous', they were able to gain new understanding of the problem statement and the properties of polystyrene, subsequently choosing hemp plastic as suitable material during design move 200.

In relating these findings to the existing literature, it seems clear that, while unguided in their endeavour to understand and solve design problems, learner designers are generally able to take an active role in developing an understanding of the design problem and generate possible solutions when communicating their thoughts to their peers (Fox-Turnbull, 2015). In the current study, the participants' verbal interactions in the STEM task context included the actions of giving each other information, proposing ideas, evaluating each other's suggestions, making judgements, and responding to their peers' questioning, which all seemed to contribute to the synthesis of their problem understanding of the problem or to generating design ideas. Not only did learners view each other as a source of information; they also used external information, including physical materials, as well as their teacher to gain a better understanding of the design task or clarify their design ideas. In this regard, these results echo previous findings that the quality of learners' thoughts in peer groups can be associated with the nature of their social and physical interactions (Marra et al., 2016; Murphy & Hennessy, 2001; Rowell, 2002). However, existing literature remains silent regarding the manner in which social and physical interactions constitute learners' thought processes.

4.4 LEARNERS' INTERACTIONS WITH CONCEPTUAL STRUCTURES

In this section, I present the results I obtained on the way in which each group of participants interacted with conceptual structures during the STEM tasks. For this study, the conceptual structures that I focused on include scientific knowledge, technological knowledge, mathematical knowledge, previous experiences and prior instances of the design process. I view these as internal information sources in terms of Extended Design Cognition (Haupt, 2015) and Activity Systems Theories (Engeström, 2015), which is embedded in my conceptual framework. In Figure 4.13, the frequency of the various groups' interactions with different conceptual structures is indicated, as executed during the STEM task.

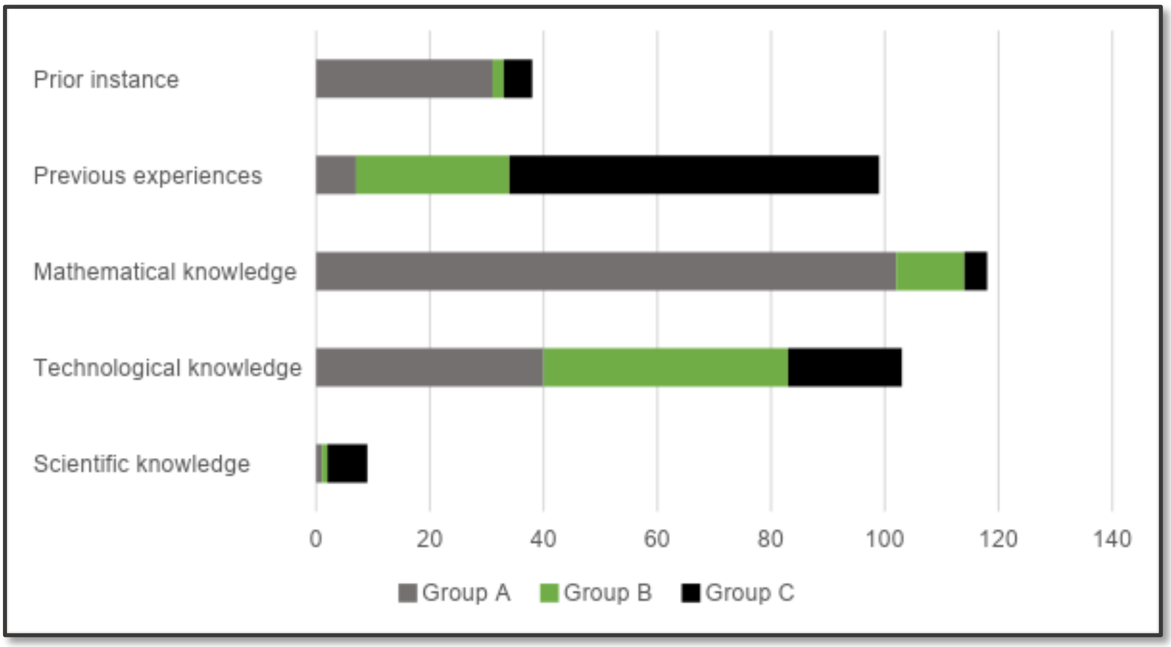


Figure 4.13: Frequency of interactions with conceptual structures for all three groups

As indicated by Figure 4.13, the number of times that each group interacted with the scientific, technological and mathematical knowledge differed. Across the groups, the participants interacted with scientific knowledge the least, with only nine design moves being generated in total, that demonstrated the use of scientific knowledge. Mathematical knowledge was used extensively by Group A (102 interactions), whereas Groups B and C had limited interactions (12 and four interactions respectively) with mathematical knowledge. All three groups made fair use of technological knowledge during completion of their STEM tasks. In terms of prior experiences, Groups B and C generated numerous design moves (27 and 65 interactions respectively) using prior experiences, while Group A's design moves were limited in this regard (seven interactions). Finally, Group A relied to some extent (31 interactions) on previously made decisions during their design process, which were recalled during their designing as part of the current study. Groups B and C on the other hand generated limited design moves (two and five interactions respectively), for which they recalled previous decisions. A summary of the number of the various design moves related to different conceptual structures is provided in Table 4.7.

Table 4.7: Number of design moves generated through interactions with different conceptual structures

Conceptual structures	Number of design moves		
	Group A	Group B	Group C
Scientific knowledge	1	1	7
Technological knowledge	40	43	20
Mathematical knowledge	102	12	4
Previous experience	7	27	65
Previous instance	31	2	5
Total	**183**	**85**	**101**

In summary, Group A generated 183 design moves in total as a result of their interactions with conceptual structures. Of these, more than 50% occurred as a result of interactions with mathematical knowledge. This predilection for mathematical knowledge was later confirmed when I analysed Group A's problem solving goals, as shown in Figure 4.14, relating these to their thinking on a suitable shape, finding suitable sizes and understanding the shape and weight of food packaging in general. In finding suitable sizes to solve the problem, Group A's use of mathematical knowledge occurred during the second half of their design process when they selected their three design ideas and were determining how big each of the proposed food containers should be.

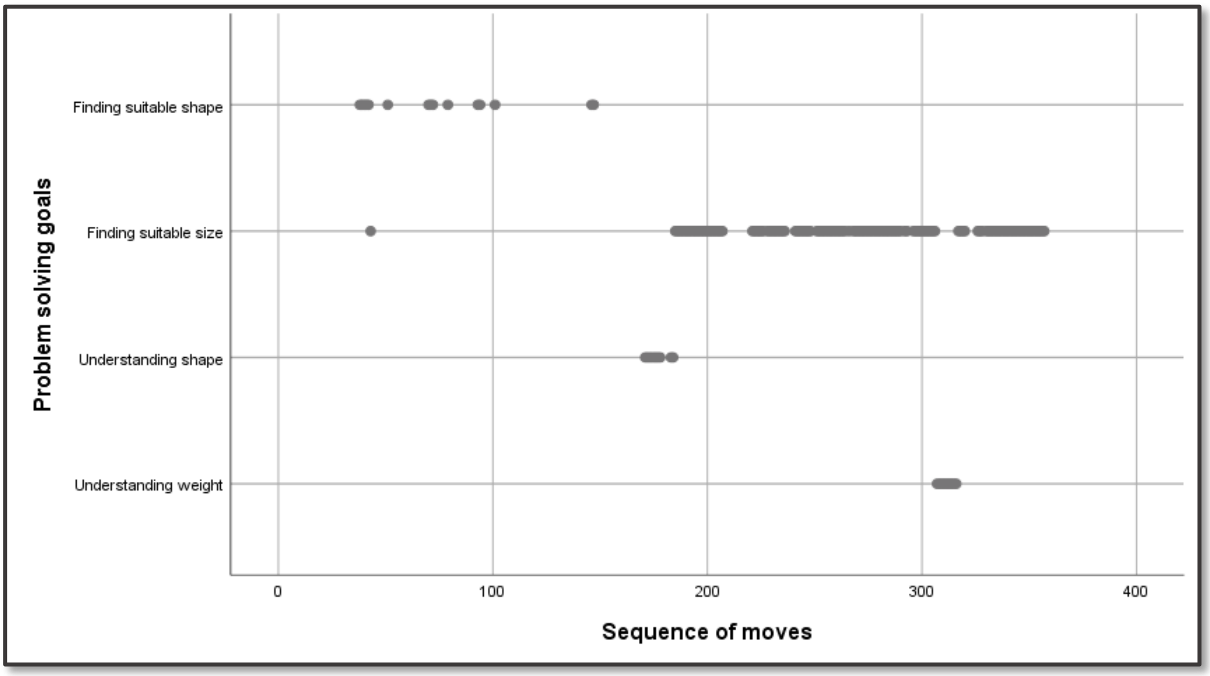


Figure 4.14: Group A’s problem solving goals, which reflects their interaction with mathematical knowledge

For Group B, Table 4.7 indicates that the participants generated the most design moves when interacting with their prior experiences and technological knowledge, with limited interactions being made with scientific and mathematical knowledge. This result is further evident from Figure 4.15, which clearly illustrates the relationship between Group B’s use of technological knowledge and prior experiences; and group members’ consideration of their problem solving goals.

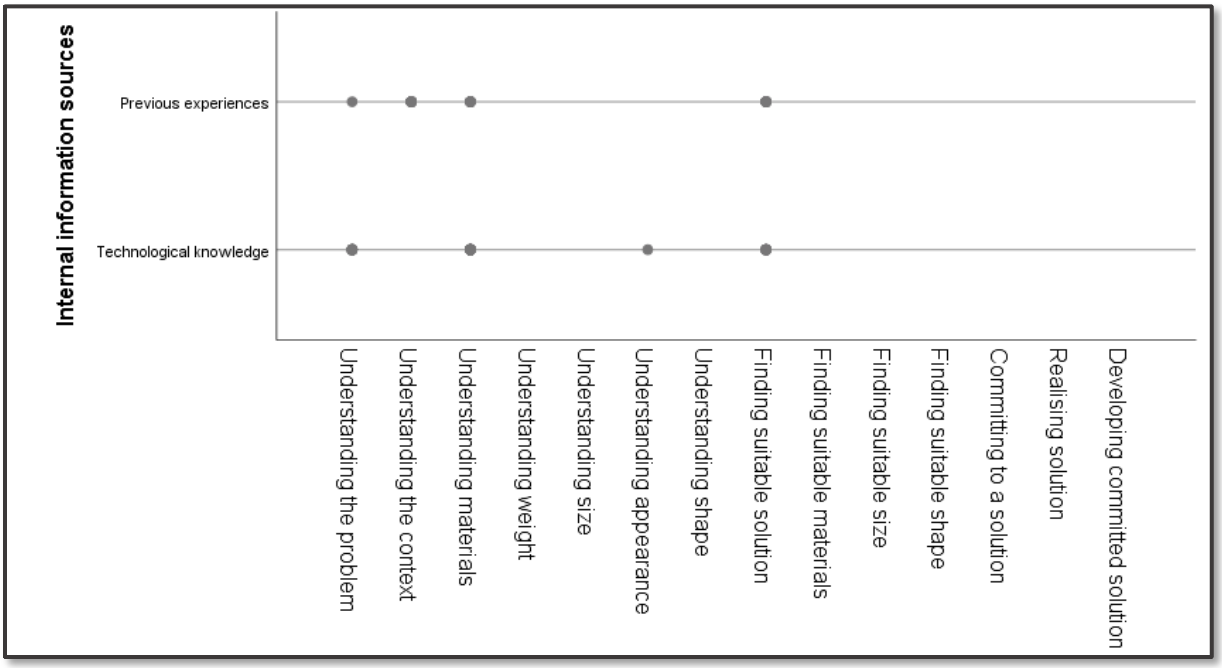


Figure 4.15: Group B's interactions with previous experiences and technological knowledge during problem solving goals

Based on the data represented in Figure 4.15, Group B specifically used their prior experiences to understand the design problem, the context and the materials for designing and making their food container, as well as when they were finding suitable solutions. In addition, more than 50% of the design moves generated by Group B's interaction with conceptual structures occurred as a result of their use of technological knowledge. Group B specifically used their technological knowledge when striving to understand their design problem, the materials, and appearance of their food container, as well as during problem solving when they were finding design solutions.

Group C was the only group that seemingly generated design moves based on their understanding of scientific principles. Similar to Group B, they predominantly used technological knowledge and previous experiences during their design process. Figure 4.16 highlights the relationship between Group C's use of scientific knowledge, technological knowledge and prior experiences, and their formulation and consideration of their problem solving goals.

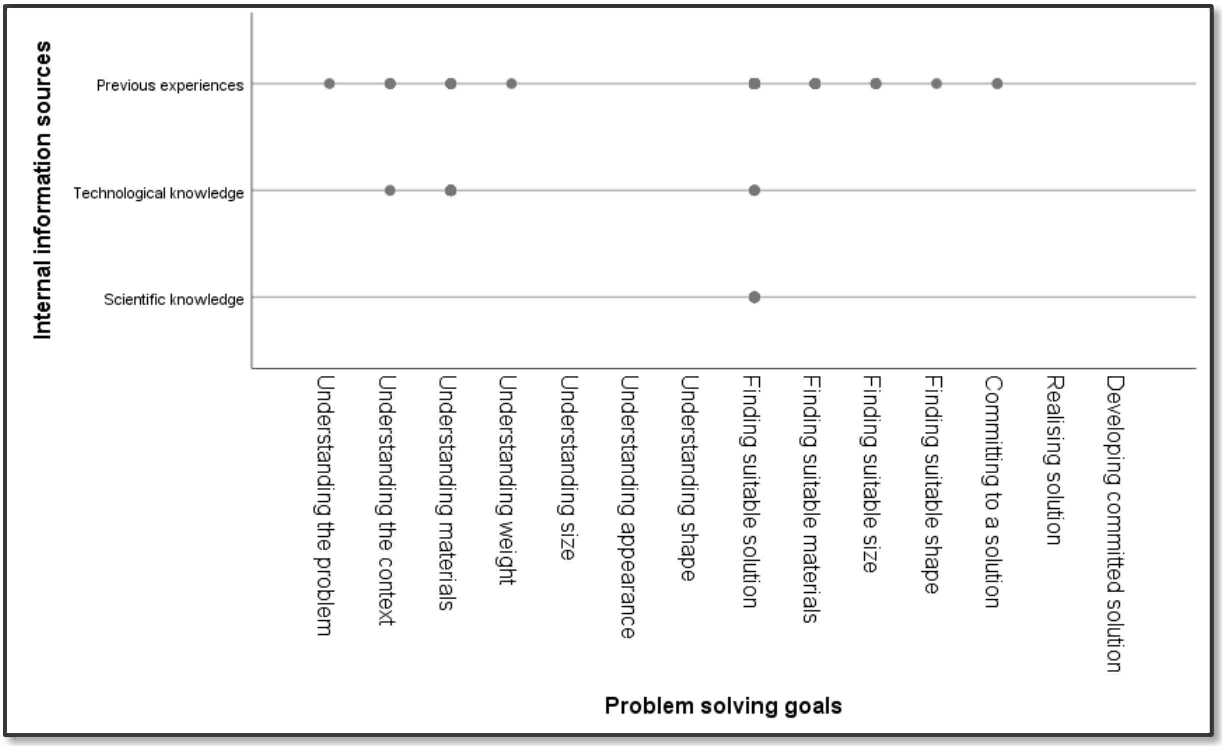


Figure 4.16: Group C's interactions with scientific knowledge, technological knowledge and previous experiences during problem solving goals

From Figure 4.16, it is apparent that the participants in Group C only used scientific knowledge during problem solving cognitive phases when they were in the process of finding suitable solutions. They also interacted with technological knowledge when attempting to understand the problem context, the materials, and find solutions. Interacting with previous experiences was similarly prevalent in their attempts to understand the problem, context, materials and weight, as well as when they were finding solutions, materials, size and shape, and when they committed to their chosen solution. In summary, Figure 4.17 provides a visual representation of all three groups and the degree to which they interacted with the various conceptual structures during the early phases of the design process, i.e. the problem structuring and problem solving cognitive phases[4].

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[4] For the purpose of this discussion I do not include leaky phases as I primarily focus on how the participants used STEM knowledge for problem structuring and problem solving respectively.

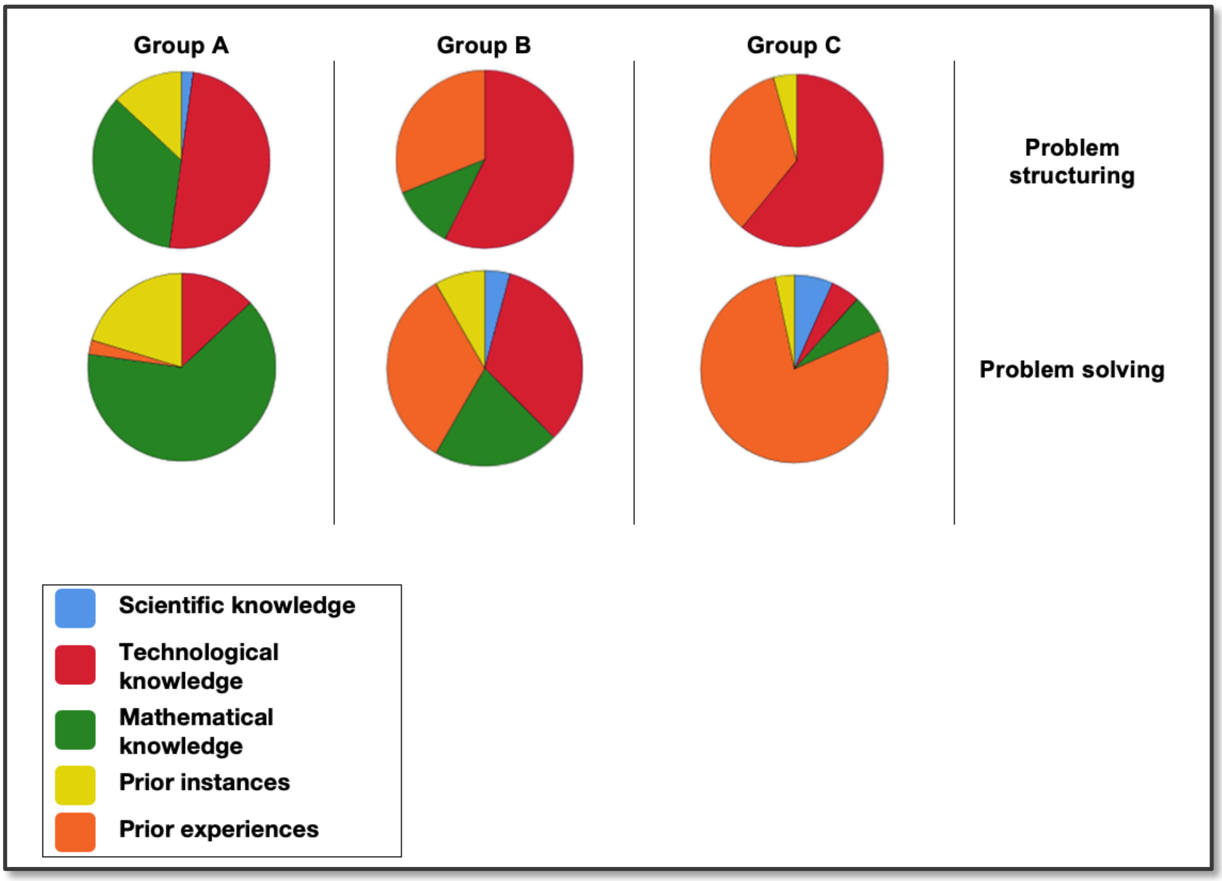


Figure 4.17: Use of conceptual structures during the early phases of the design process

In synthesising the data presented in Figure 4.17, it is clear that all three groups of participants predominantly used their technological knowledge to understand, interpret and structure their design problems. The groups rarely used scientific knowledge during the problem structuring cognitive phases. Even though Groups A and B used some mathematical knowledge during this phase, Group C did not rely on mathematical knowledge at all. Similarly, Group A hardly used any scientific knowledge, while Groups B and C used no scientific knowledge at all. It would seem, therefore, as if all three groups were able to use technological knowledge during problem structuring, whereas none of the groups were able to use scientific knowledge for this purpose.

However, during the problem solving cognitive phase, Group A relied predominantly on mathematical knowledge, as the group members spent the majority of their time on determining the size and dimensions of their proposed solutions, whereas Group B relied almost equally on technological knowledge and prior experiences for problem solving. Group C used their prior experiences with food packaging to generate and develop their design ideas, with limited interactions being made with STEM knowledge in general. From the data represented here, it thus seems clear that all of the groups used different internal information sources (conceptual structures) during problem solving cognitive phases, with no internal source being dominant.

The findings I obtained on the use of STEM knowledge during the early phases of the design process by Groups A, B and C are however contradictory to English and King's (2015) findings. These authors found that learners are most likely to use disciplinary STEM knowledge only in the later phases of the design process when engaged in prototyping, redesign and evaluation activities. In this study, however, all groups of participants extensively interacted with their mathematical and technological disciplinary knowledge during the early phases of the design process. Although the participants did not, in accordance with English and King's (2015) findings, use their scientific knowledge during the early phases, they used technological knowledge during problem structuring to make sense of their design problem and the problem context. Similarly, technological knowledge was used to identify appropriate and inappropriate materials in the making of the food container.

One of the reasons for this apparent discrepancy between what I found and what is predicted by existing literature, as well as the silence in literature on the use of scientific knowledge, may relate to the general overemphasis on scientific and mathematical ways of knowing, with less focus on understanding technological ways of knowing during STEM activities (Harrison, 2011; Kelley & Knowles, 2016). This finding emphasises the lack of sufficient research on learners’ use of knowledge and prior experiences during designing, specifically during the early phases of the design process. It seems clear that ongoing research in this area of interest is required.

In the following subsections, I further substantiate the results discussed above, by presenting examples and extracts from the qualitative data set. This is done to demonstrate how the participants in each group qualitatively interacted with the various conceptual structures in their extended design task environment during the early phases of the design process.

4.4.1 Interactions with scientific knowledge

Excerpts 4.26 to 4.28 demonstrate instances during the verbal protocols in which the participants interacted with scientific knowledge. These examples apply to both the problem structuring and problem solving cognitive phases.

P2 (move 9): So we need something to insulate?

Excerpt 4.26: Group A's use of scientific knowledge

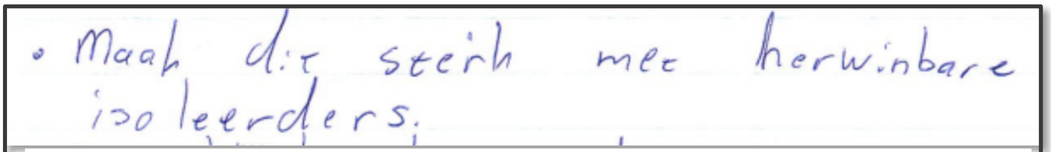
P1 (move 108): It should be a colour that absorbs heat like black

Excerpt 4.27: Group B's use of scientific knowledge

P1 (move 65): Well, it isn't. We know that since air is an insulator. If it was like this right? But then if it had layers… Because, since air doesn't easily accept or lose heat, then if it had lots of layers of air that was sealed and couldn't be opened.

Excerpt 4.28: Group C's use of scientific knowledge

The above excerpts provide supportive evidence on how each of the groups generated design moves while interacting with scientific knowledge in order to reason, understand and solve their design problem, as well as to think about future design solutions. In Group A, P2 seemed to have structured their design problem when the group reasoned that they needed to find materials that are able to prevent heat conduction from occurring, in order to keep the food warmer for longer. This was later confirmed when P1 made notes on their design requirements, as shown in Photograph 4.4.

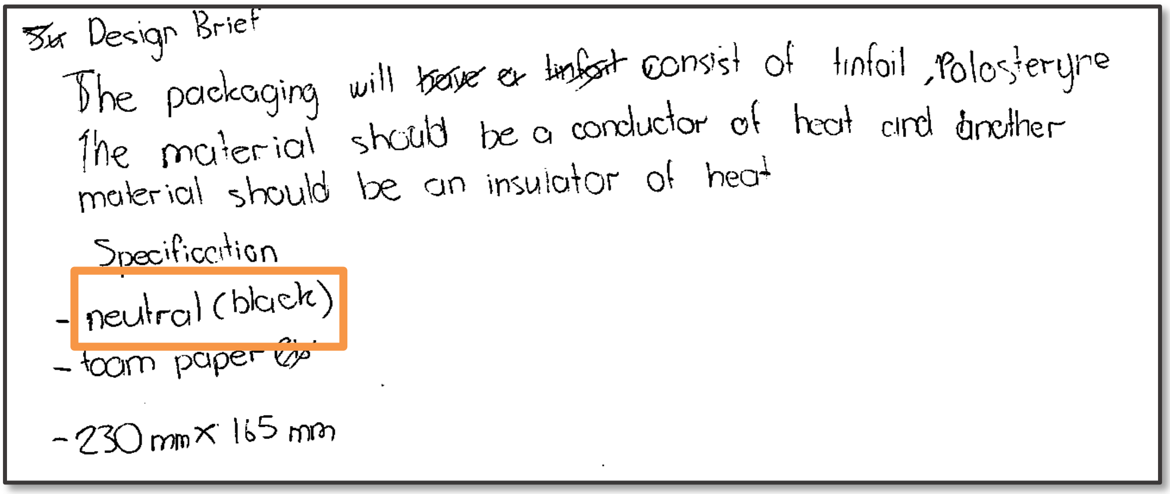


- Maak dit sterk met herwinbare isoleerders.

"Strengthening with recyclable insulators"

Photograph 4.4: Group A's use of knowledge of insulators during designing

Closely aligned, during a problem solving instance of Group B, P1 suggested that, in order to retain the heat, they should make the colour of the food container black, as black would absorb heat energy. This design choice was reiterated later in their design process, when P3 formulated the design brief, as captured in Photograph 4.5.



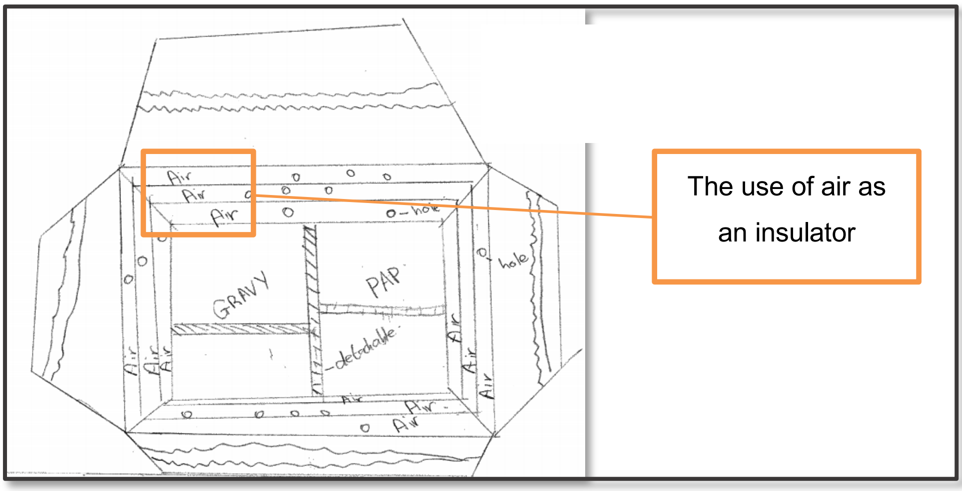
Design Brief

The packaging will ~~have~~ ~~a~~ ~~tinfoil~~ consist of tinfoil ,Polosteryne
The material should be a conductor of heat and another
material should be an insulator of heat

Specification
- neutral (black)
- foam paper
- 230 mm× 165 mm

Photograph 4.5: Group B's use a scientific principle in solving their design brief

Similarly, in Group C, P1 indicated his understanding of preventing heat conduction by suggesting the use of air as an insulator in their food container. Accordingly, this scientific principle was used throughout Group C's design process, as is evident in their sketches captured in Photograph 4.6.



The use of air as an insulator

Photograph 4.6: Group C's use of a scientific principle in drawing a design solution

As indicated in Excerpts 4.26 to 4.28 and Photographs 4.4 to 4.6, all the groups seemingly interacted with scientific knowledge in order to understand and solve their design problem.

In terms of the directionality of the design moves that were generated, Table 4.8 supports Photographs 4.4 to 4.6 in summarising the different design moves that were generated as a result of learners' interactions with scientific knowledge. The data specifically indicate that the participants did not use their scientific knowledge as general foundation of idea generation, as no group generated unidirectional forward design moves as a result of their interaction with scientific knowledge. All three groups rather used scientific knowledge only after generating initial thoughts. This means that they used their scientific knowledge to think back to previous ideas and thoughts, which led to the generation of new thoughts in the design process.

Table 4.8: Directionality of thoughts when interacting with scientific knowledge

Scientific knowledge interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	0	0
Unidirectional backward	0	0	1 (1%)
Bidirectional design moves	1 (0.5%)	1 (1.2%)	6 (5.9%)
Orphan moves	0	0	0

This finding on limited design moves being generated through interaction with scientific knowledge during designing, confirms the research of several scholars in the field (Banks & Barlex, 2014; Sidawi, 2009; Zubrowski, 2002). More specifically, existing literature emphasises the importance of teachers in supporting learners to transfer scientific concepts from the science classroom to their design projects, as learners typically struggle to do this on their own.

The limited interactions with scientific knowledge during the STEM task may be explained by means of Kimbell and Stables' (2008) black box metaphor, which indicates that learners will not necessarily have sufficient working knowledge of artefacts at the beginning of a design process. As this study was situated in the early phases of the design process, in-depth knowledge of design components was not a prerequisite for the participants. However, further research on how learners use scientific knowledge during the early phases of the design process is required, especially on how their understanding of scientific concepts may develop during the early, middle and later phases of the design process.

4.4.2 Interactions with technological knowledge

In Excerpts 4.29 to 4.31, I include examples of instances in the verbal protocols where the participants interacted with technological knowledge during the problem structuring and problem solving phases.

P3 (move 30): May I ask can we take out the materials that are not biodegradable? Then we can work with those that are biodegradable.

Excerpt 4.29: Group A's use of technological knowledge

P3: (move 57) It's a design brief, it's our actual design. So, take out all the parts that we are using in our design and write them in the form of a paragraph.

P3: (move 84) No I think I made a mistake. Design brief shouldn't be a list of parts, it should be the reason why we're designing and building it then.

Excerpt 4.30: Group B's use of technological knowledge

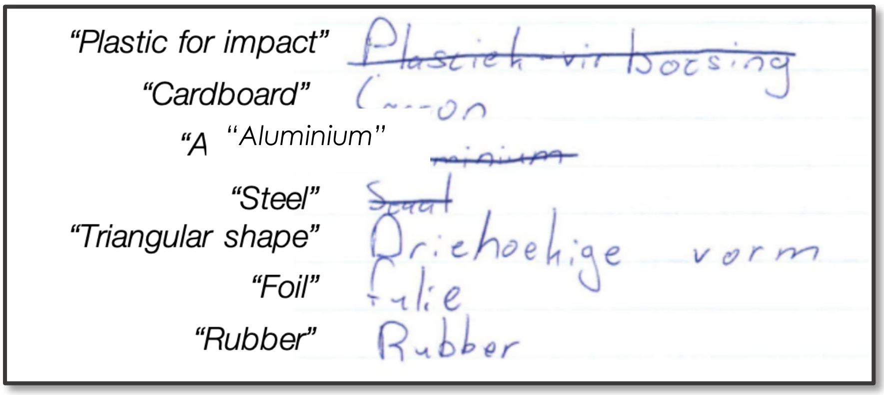
P1: (move 12) What about rubber?

P1: (move 13) Rubber is good for keeping heat in

P3: (move 14) And, it can also be cleaned easily

Excerpt 4.31: Group C's use of technological knowledge

In these excerpts, the participants interacted with technological knowledge in a way that could assist them to make design choices. For example, in Excerpt 4.29, P3 asked the other participants in Group A to eliminate non-biodegradable materials from a list of possible materials that could be used for making a heat retaining food container. This elimination was done on a piece of paper and is captured in Photograph 4.7.



“Plastic for impact”	~~Plastiek vir botsing~~
“Cardboard”	[illegible]on
“A “Aluminium”	~~minium~~
“Steel”	~~Staal~~
“Triangular shape”	Driehoekige vorm
“Foil”	Folie
“Rubber”	Rubber

Photograph 4.7: Group A’s elimination of non-biodegradable materials

Photograph 4.7 therefore demonstrates how Group A interacted with technological knowledge in order to eliminate certain materials, including plastic, aluminium and steel. P1 did not, however, eliminate aluminium foil, as they at that stage shifted their attention to a recyclable design intention rather than a biodegradable one, as already indicated and discussed in Excerpt 4.20.

In the case of Group B, P3 read the instruction from the problem statement to write a design brief (Excerpt 4.30), suggesting that the design brief should list the different physical parts of a design solution during move 57. However, as their discussion progressed, he corrected himself in design move 84 by stating that their design brief should rather indicate the reasons for designing and making the food container. In this manner, P3 interacted with technological knowledge in terms of his understanding of a design brief and corrected himself when he realised that he had provided an incorrect description of the design brief.

Excerpt 4.31 similarly demonstrates how P1 in Group C interacted with technological knowledge. While gazing at the tools and materials in the learning environment to explore biodegradable materials for making their food container, P1 proposed rubber as potentially suitable material. In justifying his proposal, he recalled his technological knowledge on the thermal properties of rubber, indicating that rubber is good for insulating heat. Subsequently, P3, in support, justified the use of rubber based on the design requirement that it had to be easy to clean.

In summary, Excerpts 4.29 to 4.31 thus illustrate how the participants in all three groups interacted with technological knowledge in order to be able to make design choices about possible materials they could use in making a heat retaining food container. In addition, Group B interacted with technological knowledge to understand and execute the problem statement instructions and to formulate a design brief. This finding is summarised in Table 4.9, which captures the direction of generated thoughts in terms of the learners' interactions with technological knowledge.

Table 4.9: Directionality of thoughts when interacting with technological knowledge

Technological knowledge interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	3 (1.6%)	4 (4.7%)	3 (3%)
Unidirectional backward	9 (4.9%)	12 (14.1%)	7 (6.9%)
Bidirectional design moves	29 (15.8%)	27 (31.8%)	10 (9.9%)
Orphan moves	1 (0.5%)	0	0

The data captured in Table 4.9 once again illustrate that all three groups used technological knowledge to generate new thoughts, as shown in the unidirectional forward moves. Learners seemingly used technological knowledge solely for the purpose of reflection or evaluation purposes, as indicated by the number of unidirectional backward moves. The majority of the moves were bidirectional, meaning that the learners were able to reflect back on previously generated thoughts, while generating new thoughts and ideas about their understanding of the problem or their design solutions. Only one orphan move was generated, implying that the thoughts generated from technological knowledge were connected to previous thoughts.

Based on the results I obtained, it seems evident that the various groups implemented different strategies in interacting with technological knowledge. Group A apparently employed the complementary principle of extended cognition, as explained by Sutton (2010), when they offloaded internal information in the task environment, which the group of participants could subsequently collectively evaluate externally. Group B utilised corrective practice, as suggested by Menary and Gillet (2017), when during a group discussion, realised that they had not formulated the design brief correctly. Finally, Group C demonstrated the object-orientedness principle of Activity Systems Theory as proposed by Kaptelinin and Nardi (2006), when they were goal-directed to find a material with heat insulating properties, that was also biodegradable.

This finding, highlighting the unique ways in which the learners in this study interacted with technological knowledge, supports existing literature on Extended Design Cognition Theory (Haupt, 2015; Ingold, 2010; Jornet & Roth, 2018). It demonstrates that learners' way of interaction with technological knowledge cannot necessarily be predicted, neither can it be universalised, as the goals of the design task, the availability of internal and external information sources in the design task environment, as well as learners' prior design experiences will all affect the way in which they interact with knowledge. Furthermore, from an Extended Design Cognition viewpoint, Groups A and B's interactions with technological knowledge was seemingly dependent on physical structures in their learning environment, and generated several productive thoughts during interaction. This finding is supported by my conceptual framework, which highlights the open-systems perspective to design cognition (Backlund, 2000; Kitto, 2014), as well as the crucial role that external information sources may play during effective designing (Haupt, 2015).

4.4.3 Interactions with mathematical knowledge

In Excerpts 4.32 to 4.34, three examples are provided of instances where the participants of each group interacted with mathematical knowledge during the STEM task.

P1: This is a pentagon right?

P3: No, a pentagon has five sides

P1: Hexagon?

P2: How many sides does it have, eight?

P3: There are eight sides

P2: Octagon

P1: No, there are six sides

P2: There is six? Rubbish man

P1: 1, 2, 3, Oh. No. So it is a octagon

Excerpt 4.32: Group A's use of mathematical knowledge

P1: (Using a ruler), twenty, twenty, twenty… Two hundred and thirty millimetres.

P3: This size (points to the length of the foil container) times

P1: One sixty, one hundred and sixty five millimetres

Excerpt 4.33: Group B's use of mathematical knowledge

P1: It needs to be relatively short if it's easy to carry. If we have, um, what's this? What are these (looking at the ruler)? Millimeters? So millimeters. Ok, let me just hold them centimeters.

P1: If we have it this long, say this long. 14 cm, right?

P2: That's quite short. You see, I think it should be, about, you know, 20, long. If it should be able to carry 1.1.

P1: Ok if we, make it. Let's say we work with 14. Around this. How long will it have to be on the side? Say it's 14 on this side, maybe another 14 on that side?

P2: Shouldn't this one be a bit longer. Like here, this will come, this one's 14 but this one's 20.

P1: 20. Jo, 20 is long, man.

P2: Yeah I know. If you put it like here. See. I still think it's gonna be quite a small one.

Excerpt 4.34: Group C's use of mathematical knowledge

In Excerpt 4.32, Group A's participants interacted with mathematical knowledge in order to correctly identify a 3D shape, which they wanted to use as a shape for their design solution. Prior to this instance, Group A initially identified the octagonal shape as suitable for a food container when they looked at Figure 14 (presented here below as Figure 4.18) in their problem statement instructions.

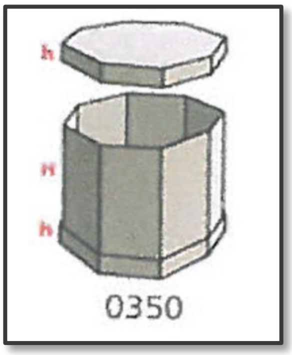
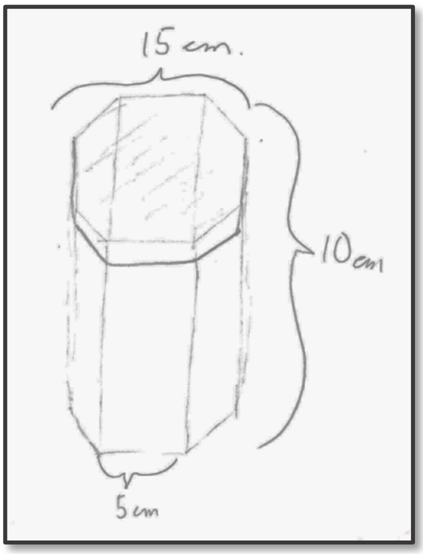


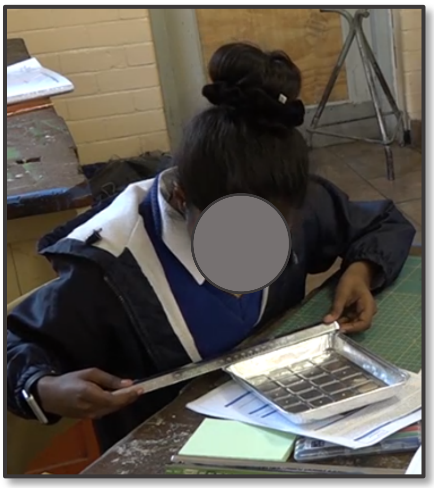
Figure 4.18: Octagonal prism food container (Figure 14 in STEM task)

When P1 looked at Figure 14, he first identified it as a pentagon. However, P3 corrected him by stating that a pentagon has five sides, which prompted P1 to ask if it is a hexagon. In order to correctly identify the 3D shape, P2 inquired about the number of sides of the container. He then identified it as an octagon based on the indication of eight sides by P3. However, P1 was still of the opinion that there were only six sides, yet after physically counting the sides on Figure 14, he realised that there are indeed eight sides, confirming P2's view of the shape being an octagonal prism. After identifying the 3D shape as an octagonal prism, Group A selected this idea as one of their design concepts, which they developed later on in the design process. Their concept is captured in Photograph 4.8.

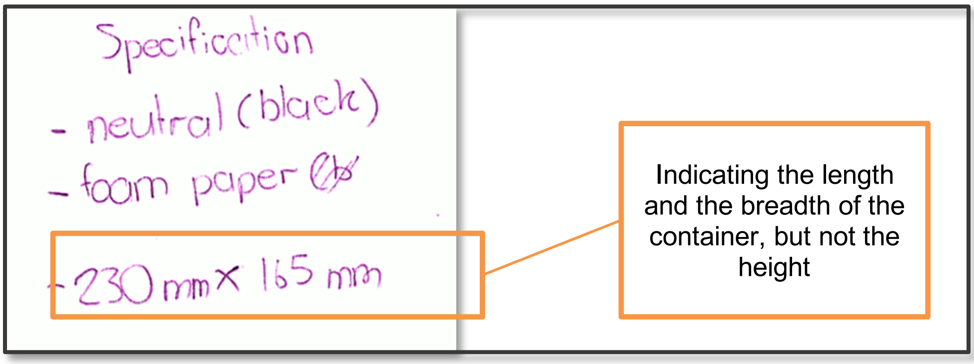


Photograph 4.8: Group A's octagonal prism idea with measurements

Group B's interaction with mathematical knowledge is captured in Excerpt 4.33, indicating how they attempted to find a suitable size for their food container. The participants of Group B namely used a ruler to measure the length and breadth of an existing foil container, yet seemingly forgot to measure the height of the container. Photograph 4.9 captures the moment in which P1 took the ruler and started measuring the foil container, while Photograph 4.10 depicts P3's notes on the length and breadth of this food container as per the specification list.



Photograph 4.9: Measuring a foil container



Specification
- neutral (black)
- foam paper
- 230 mm × 165 mm

Indicating the length and the breadth of the container, but not the height

Photograph 4.10: Group A's measurements of the food container

In Excerpt 4.34, similar to Group B, Group C's participants were also in the process of finding a suitable size for their food container, however, they followed a different strategy to determine a suitable size. At first, P1 determined the units in which the ruler measures, as captured in Photograph 4.11[5]. Hereafter, P1 used the ruler and a guess and test strategy to propose 14cm as a suitable length for the container. However, P2

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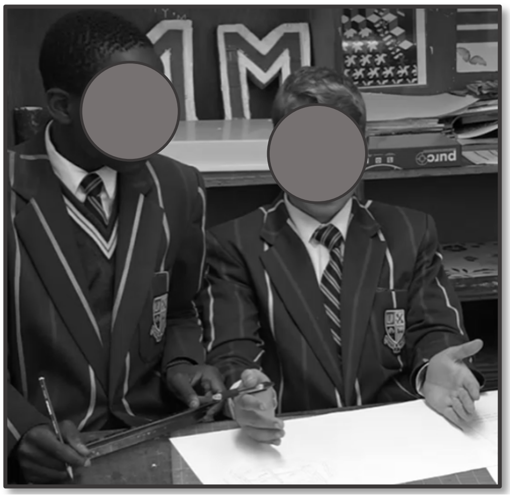
[5] For the sake of anonymity of School C, Photographs 4.11 and 4.12 are printed in black and white.

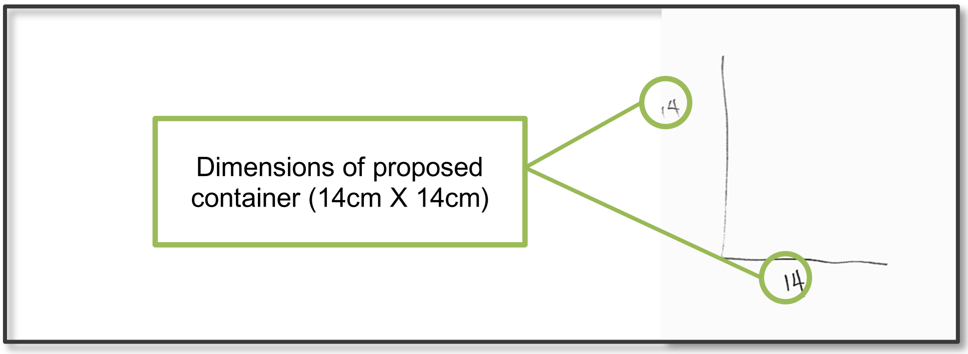
did not agree with P1's proposal and estimated 20cm by using his hands. He then proposed 20cm as a suitable length for the container, as shown in Photograph 4.12.

Photograph 4.11: Inspecting the units on the ruler



Photograph 4.12: Proposing 20cm as suitable length for the food container

However, P1 ignored P2's proposal of 20cm and continued to find a suitable size for the container based on his idea of 14cm. In the next design move, P1 started making a drawing (Photograph 4.13) in modelling his idea for the size of the container.



Photograph 4.13: Drawing to determine the size of the container

In response, P2 continued the discussion by agreeing to the breadth of the container being 14cm, but proposed a length of 20cm. After a while, this process of reasoning about the size of the container subsided, and was as a result not reflected in the final design brief.

In Table 4.10, the learners' use of mathematical knowledge throughout the design process is captured. In summary, Group A generated several thoughts based on their interaction with mathematical knowledge. The majority (44.8%) of these thoughts were bidirectional in nature, which indicates that the participants accessed previous thoughts while generating new thoughts on a continuous basis. In this case, the thoughts that were generated centred on the sizes of the three chosen design ideas. Groups B and C did not interact much with their mathematical knowledge in comparison to Group A. Furthermore, Group B mostly generated unidirectional backward moves, which implies that they mainly used mathematical knowledge to evaluate previously generated thoughts about the size and weight requirements of their designs. Closely aligned, Group C generated limited thoughts based on their existing mathematical knowledge.

Table 4.10: Directionality of thoughts when interacting with mathematical knowledge

Mathematical knowledge interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	1 (1.2%)	0
Unidirectional backward	20 (10.9%)	7 (8.2)	1 (1%)
Bidirectional design moves	82 (44.8%)	4 (4.7%)	3 (3%)
Orphan moves	0	0	0

As illustrated by Excerpts 4.32 to 4.34, and Photographs 4.8 to 4.13, and Table 4.10, all of the groups were seemingly able to collaboratively interact with mathematical knowledge during the design process. In all three cases, the participants interacted with mathematical knowledge, while simultaneously interacting with physical structures. Group A demonstrated how a participant utilised a diagram of an octagon to complete the cognitive task of remembering the name of a shape (Heersmink, 2016). In searching for suitable dimensions for their food container, Group B demonstrated the integration principle of extended cognition (Sutton, 2010; Menary & Gillet, 2017) when they used a ruler to measure an aluminium tinfoil container in order reach to address their goal of finding a suitable size. Finally, Group C demonstrated Menary's (2011) representational system principle, whereby a person can use sketches, notes or 3D modelling to complete cognitive tasks, while interacting with mathematical knowledge.

This finding aligns with the findings of other studies in mathematics education, which indicate that learning in collaborative settings may assist students to develop ways of thinking by appropriating their group members' ways of talking and acting (Carlsen, 2010; Lai & White, 2012). Furthermore, this finding supports the notion of an extended design task environment in my conceptual framework. In terms of Activity Systems Theory (Engeström, 2015), this finding also shows that external tools may mediate learners' goal oriented activities when working toward addressing a specific design problem solving goal (Stevenson, 2004).

However, the findings in design and technology education literature are still emerging in terms of the way in which learners can use mathematical concepts in the early phases of designing. These phases are crucial according to Tank et al. (2018), since this is where learners can acquire knowledge on a design problem as they gather mathematical knowledge, while exploring what has already been done to solve the problem. Ongoing research on the role that mathematical knowledge may play during the early phases of the design process is therefore required.

4.4.4 Interactions with prior experiences

The participants' interactions with their prior experiences included forward and backward moves in their thought processes while trying to make design choices and find suitable designs.

P2 (move 94): Are we going to create a space for a water bottle or a bottle with cold drink in it?

P1 (move 95): What? What are they selling? Because they are not a McDonald's!

Excerpt 4.35: Group A's use of prior experiences

P2 (move 64): The aluminium has to be inside of the container not outside. But we must cover it so it must not shine too much.

P1 (move 65): I was thinking polystyrene or cardboard?

P2 (move 66): Yes. Because I've seen how those people walk in the sun. So when they walk in the sun it will shine too much.

Excerpt 4.36: Group B's use of prior experiences

P2 (move 192): I was thinking, you know when Mam talked about the hemp plastic? We can use that?

Excerpt 4.37: Group C's use of prior experiences

Excerpts 4.35 to 4.37 provide qualitative support for the way in which the various groups generated design moves in interaction with their prior experiences. In Excerpt 4.35, P2 for example proposed to the group that they could consider the inclusion of a space for a cold drink bottle in the food packaging. However, this proposal was met with resistance by P1, who evaluated P2's proposal when he mentioned that food vendors were not like McDonald's, referring to his previous experience with a popular fast food restaurant. In this way, P1 reminded P2 of the problem context.

In Excerpt 4.36, while thinking about the appearance of their food container, P2 evaluated the existing aluminium containers in the task environment and suggested that, if they were to use aluminium foil to make a food container, it should form the inside and not the outside of the container. Subsequently, P1 proposed that the group could use either cardboard or polystyrene as a suitable cover material. P2 elaborated on the need to cover the outside of the container, as she recalled a prior experience of walking outside, with aluminium foil which reflected the sun, thereby resulting in an unpleasant experience. Finally, for Group C, Excerpt 4.37 shows how, while thinking of possible materials to make a food container, P2 remembered an instance where his technology teacher showed them a video of hemp plastic, which is biodegradable, and could offer a suitable alternative material to plastic. The nature of the learners' interactions with previous experiences is further evident in Table 4.11.

Table 4.11: Directionality of thoughts when interacting with previous experiences

Prior experience interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	0	5 (5%)
Unidirectional backward	2 (1.1%)	10 (11.8)	15 (14.9%)
Bidirectional design moves	5 (2.7%)	17 (19.6%)	44 (43.6%)
Orphan moves	0	0	1 (1%)

As captured in Table 4.11, Group C was the only group that used their previous experiences when generating unidirectional forward moves, as also shown for example, in Excerpt 4.37, when they generated a new thought about using hemp plastic as a biodegradable alternative to plastic. On the other hand, Groups A and B used their previous experiences to evaluate previously generated thoughts about the design problem solving context and design ideas, as shown in the generation of unidirectional backward moves. Groups B and C were furthermore able to generate bidirectional moves based on their interactions with their previous knowledge, continuously shifting between generative and evaluative thoughts during designing. This implies that when the participants of Groups B and C interacted with their previous experiences, they were able to use this to evaluate previously instantiated thoughts, but also to generate new avenues for thinking.

In Excerpts 4.35 to 4.37 and Table 4.11 I thus include qualitative and quantitative evidence on the finding that the participants could rely on their prior experiences for generating and evaluating thoughts when engaging in the design task. This finding is further supported by existing literature (Fox-Turnbull, 2015; Milne & Edwards, 2013). For example, the funds of knowledge in technology education movement refers to the information, knowledge and skills that learners generally access and use during designing, which in turn relate to their culture, home, and community (Fleer & Quinones, 2009; Fox-Turnbull, 2015; González, Moll & Amanti, 2005). Previous studies (Carr, 2001; Fox-Turnbull, 2016; Milne & Edwards, 2013) in technology education indicate that a focus on learners' everyday contexts may allow teachers to not only gain insight into the learners' funds of knowledge, but also to use these funds of knowledge in meaningful ways of knowledge instruction in the classroom.

From an Activity Systems Theory perspective (Engeström, 2015), my investigation of learners' previous experiences assisted me to locate the participants' contexts and how they used this contextual knowledge during designing. This further supports a distinct knowledge type in technology education, namely that both professional designers and novice designers use socio-technological knowledge (Ropohl, 1997) or situational knowledge (Venselaar et al., 1987). However, the way in which this knowledge is used in technology classrooms and STEM activities has not gained sufficient coverage in the literature. As such, further research is necessary to determine the extent to which this knowledge type may support or impede learners' design cognition.

In the preceding sections, I discussed how each group of participants interacted with conceptual structures during the early phases of the design process. Of particular significance was the way in which the participants used their STEM knowledge and prior experiences (internal sources) to structure and solve the STEM task.

4.5 CONCLUSION

In this chapter, I discussed the general linkography results of the three different cases, which were situated in three medium-resourced schools. I also presented my findings on the social and conceptual interactions of participants. Of significance is the finding that Groups A and C engaged in bidirectional thinking, similar to that of expert designers. However, none of the groups exhibited sufficient critical backward design moves, which implies that they did not evaluate or significantly reflect on their generative thoughts. The results furthermore indicate that the participants in each group were dependent on each other's design moves, suggesting that their design moves constituted each other's cognitive processes. In terms of the participants' interactions with conceptual structures, I found that learners actively engaged with technological knowledge, but rarely engaged with their existing scientific knowledge. As mentioned previously, this could potentially be due to the fact that scientific knowledge is usually only interacted with during the later phases of the design process.

In the next chapter, I report on the second part of my results and findings. More specifically, I investigate each group of participants' interactions with physical structures in order to explore how their design processes emerged. I conclude my discussion on findings with a discussion on how learners interactively used physical and conceptual structures.

CHAPTER 5

RESULTS AND FINDINGS ON PHYSICAL STRUCTURE INTERACTIONS

5.1 INTRODUCTION

In Chapter 4, I presented the general linkography results, as well as the results and findings pertaining to the social and conceptual interactions that occurred within the groups of participants. I discussed the results in terms of what I obtained, and related the results to the current body of knowledge.

In this chapter, I present and discuss the results and findings of the three groups of learners' physical interactions during the design processes they completed. In addition, I discuss the findings related to the participants' interactions between conceptual and physical structures. Throughout, I situate my results within existing literature and the conceptual framework that guided my study.

5.2 LEARNERS' INTERACTIONS WITH PHYSICAL STRUCTURES

In this section I focus on the interactions of the participants with external information sources or tools against the background of the Extended Design Cognition and Activity Systems Theories. As an introduction to my discussion, Figure 5.1 and Table 5.1 provide an overview of the frequency and percentage of each group's interactions with different physical structures, in other words, with external information sources.

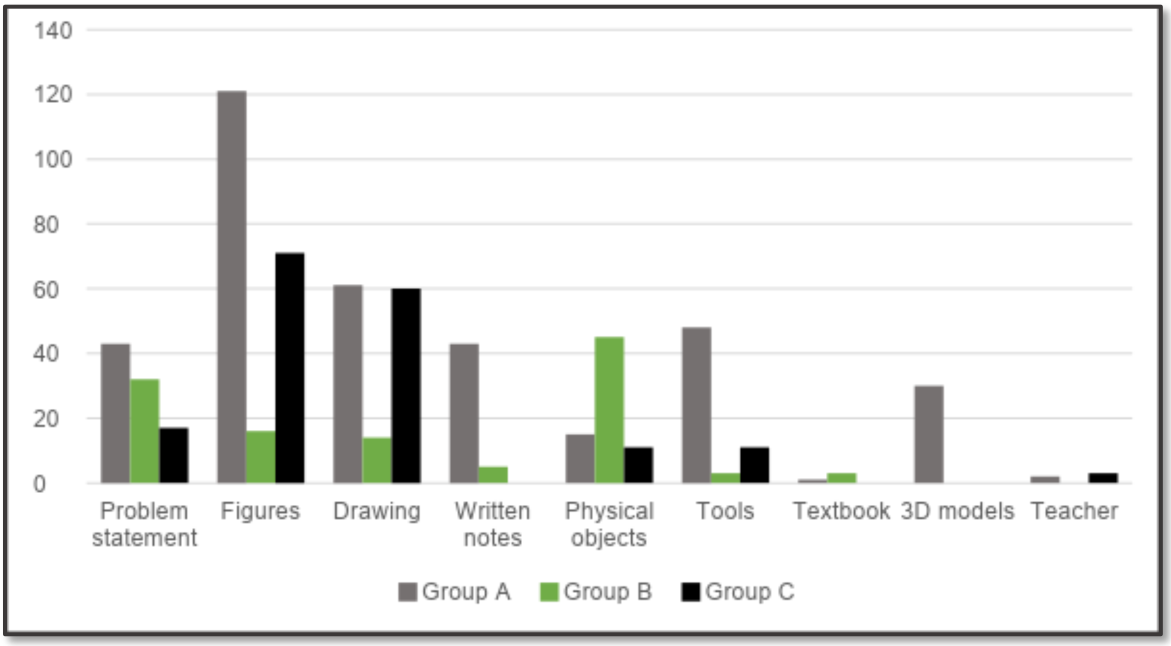


Figure 5.1: Frequency use of external information sources

Table 5.1: Frequency and percentage of interaction with physical structures

	Group A		Group B		Group C	
	Frequency	**%**	**Frequency**	**%**	**Frequency**	**%**
Problem statement	43	11.8	31	27.1	17	9.8
Figures	121	33.2	16	13.6	71	41
Drawing	61	16.8	14	11.9	60	34.7
Written notes	43	11.8	5	4.2	0	0
Physical objects	15	4.1	45	38.1	11	6.4
Tools	48	13.2	3	2.5	11	6.4
Textbook	1	0.3	3	2.5	0	0
3D models	30	8.2	0	0	0	0
Teacher	2	0.5	0	0	3	1.7
Total	**364**	**100**	**118**	**100**	**173**	**100**

When examining the data captured in Figure 5.1 and Table 5.1, it can be seen that both Groups A and C predominantly interacted with figures and drawings during their design processes, while Group B primarily interacted with physical objects and problem statement instructions. All three groups barely interacted with their teachers and textbooks to structure or solve the STEM task. As a result, it appears as if the participants mostly engaged most with temporarily provided external information sources while not really accessing the ever-present available sources of their teachers and textbooks.

In my attempt to understand how the groups of participants utilised the external information sources, I also investigated how they used these during the respective cognitive phases. Figures 5.2 to 5.4 indicate the frequency of Groups A, B and C's interactions with external information sources during the early phases of the design process. My discussion of these results follow the respective figures.

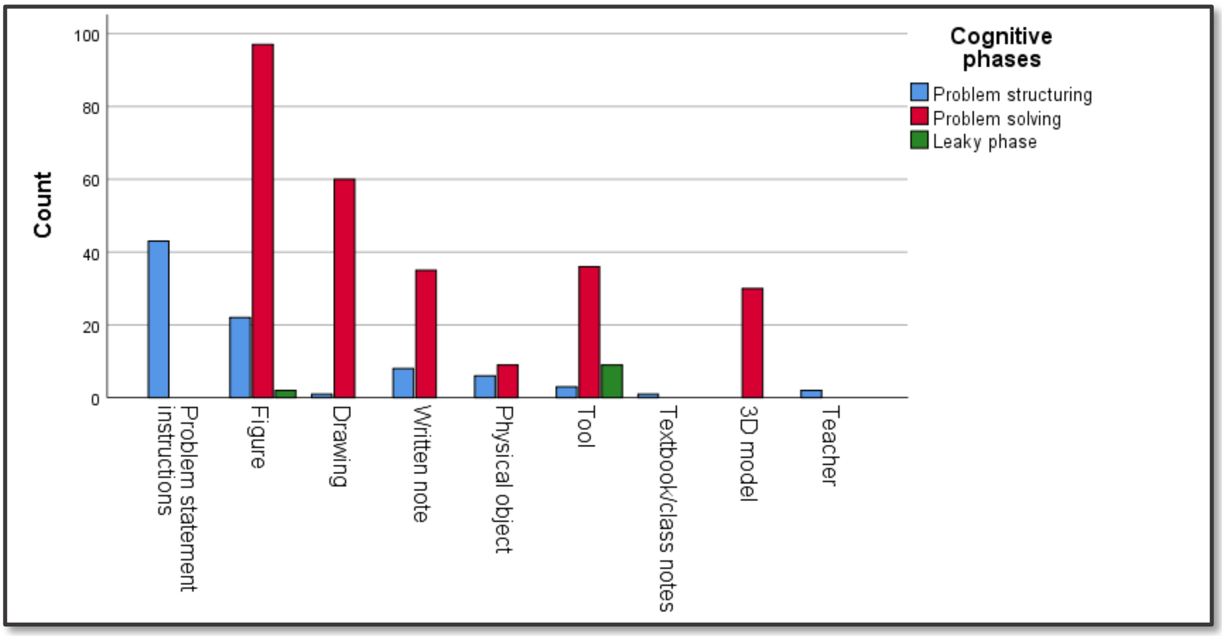


Figure 5.2: Group A's use of external information sources during the early phases of the design process

Group A frequently interacted with their problem statement and figures during the problem structuring cognitive phases, while relying mostly on figures and their own drawings during the problem solving cognitive phases. Figure 5.2 specifically highlights that Group A was primarily focused on problem solving during their use of external information sources, except during problem structuring, when they interacted exclusively with the problem statement instructions. However, this was not the case with Group B's interactions with external information sources, as captured in Figure 5.3.

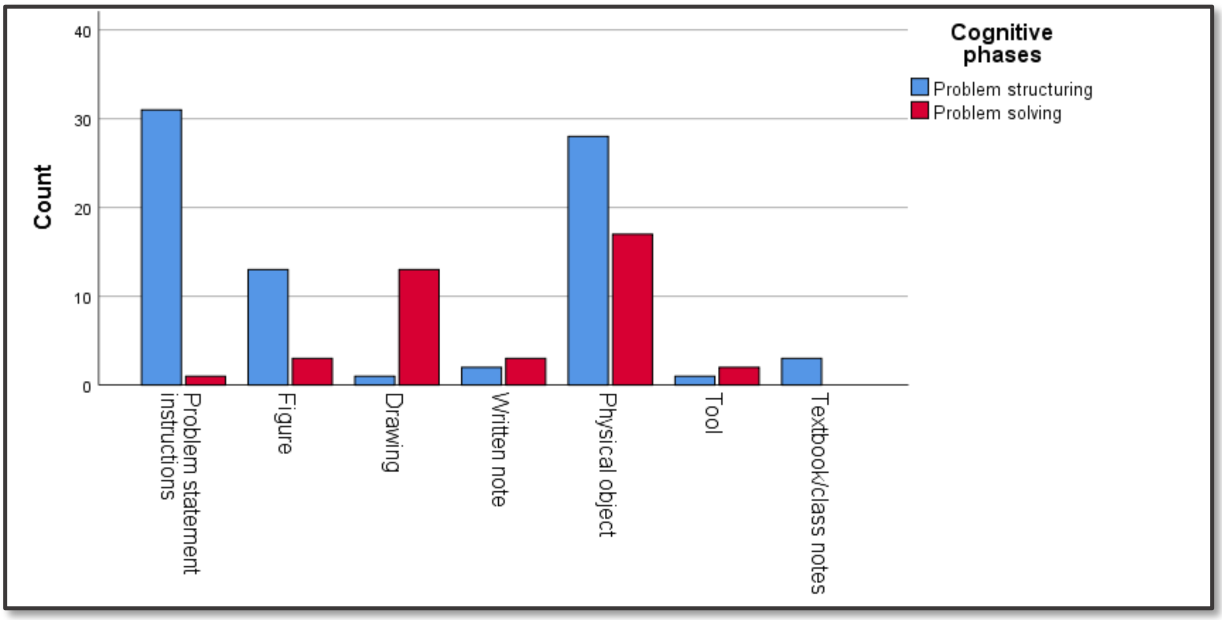


Figure 5.3: Group B's use of external information sources during the early phases of the design process

Figure 5.3 indicates that Group B largely engaged in the problem structuring cognitive phases when interacting with external information sources. A much lower degree of interaction with problem solving however occurred and no evidence exists on the presence of any leaky phases. In terms of information sources, Group B primarily interacted with the problem statement and physical objects in the design task environment to structure their problem, while mostly relying on their drawings and physical objects during problem solving. Group C yet again presented a completely different scenario, as captured in Figure 5.4, and more closely aligned with Group A rather than Group B.

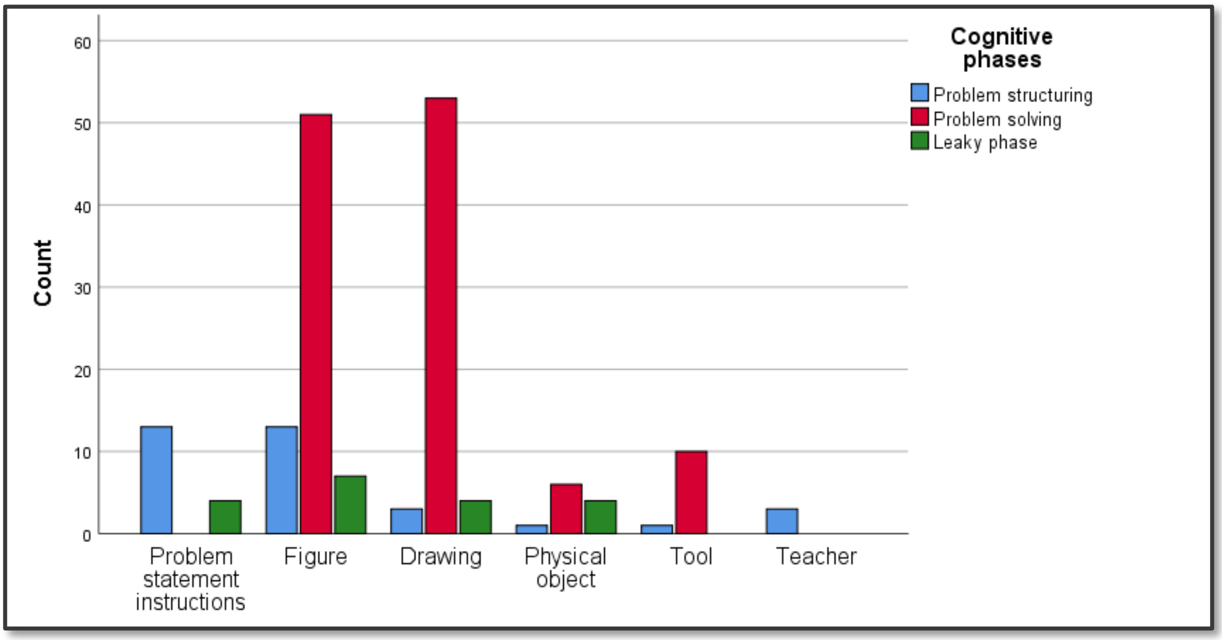


Figure 5.4: Group C's use of external information sources during the early phases of the design process

Similar to Group A, Group C thus also predominantly used their problem statement instructions and figures to understand the design problem. They mostly interacted with figures and drawings during the design problem solving cognitive phases, with their interaction with other sources being limited and, as in the case of physical objects, barely evident.

In considering the results I obtained on the three groups' interactions with physical structures, it seems apparent that during the early phases of the design process, learners in the unguided environment typically used their problem statements and figures provided to them about the problem context as part of the STEM task, existing solutions and scientific principles to structure and frame their design problems. They furthermore used drawings, tools and physical objects as tools to solve their design problems.

These findings support my decision to use Extended Design Cognition Theory (Haupt, 2015) as underlying framework for this study. More specifically, in linking these findings to existing literature, the tendency of the participants to rely on external information embedded in the physical environment to guide their designing is supported by various other studies that typically include sketches (Härkki et al., 2018;

Hope, 2008; Kelley & Sung, 2016), 3D modelling (Barak & Zadok, 2009; Welch et al., 2000; Worsley & Blikstein, 2016), writing (Druin & Fast, 2002; Mavers, 2011), and pictorial information (Gates, 2018; Ginns et al., 2005). However, the way in which these physical structures affect learners' design cognition during the early phases remain elusive as limited theoretical frameworks exist to study how such structures form part of learners' cognitive processes (Howard-Jones & Jay, 2014; Middleton, 2008; Petrina, 2010), especially during the early phases of designing.

As such, this current study's use of Extended Design Cognition Theory (Haupt, 2015) contributes an adapted framework for understanding learners' engagement with physical structures during designing, while also considering social and conceptual structures in the environment. In the following subsections, I provide extracts from the qualitative data set to illustrate how the participants in the various groups interacted with the different physical structures in their design task environments.

5.2.1 Interactions with the problem statement

Excerpts 5.1 to 5.3 capture instances during which the participants interacted with their problem statements when completing the STEM task.

P3 (move 64): Right what is the problems that need to be solved? How can we solve it?

Excerpt 5.1: Group A's interactions with the problem statement

P3 (move 10): So, start by the first question, né. What is the problem or problems that needs to be solved and how can we solve it?

Excerpt 5.2: Group B's interactions with the problem statement

P2 (move 147): It has to carry what? How much does it need to be able to contain?

Excerpt 5.3: Group C's interactions with the problem statement

These excerpts demonstrate how the different groups employed different ways in utilising the problem statement instructions during the STEM task. Groups A and B for example used their problem statement as a tool to progress in terms of their thinking about the design problem and solution. This is supported by Activity Systems Theory (Engeström, 2015), according to which the problem statement can be viewed as a mediating tool between the subjects (participants) and the design object (understanding the problem, finding solutions etc.). In this way, Groups A and B used the problem statement and its guidelines as a tool to progress in their design process. The guidelines that were provided required of them to think about the design problem context, to write a design brief and specification list, to generate at least two or three design ideas, and to build their selected design ideas.

Group C, however, followed a different approach as they apparently did not address the guidelines in the problem statement in a systematic manner. Instead, they primarily used the problem statement as a source of information to either obtain information about the requirements and constraints of designing the food container, or to evaluate their decisions after making them. This result supports the Extended Information Processing Theory of designing (Haupt, 2015), which is embedded in my conceptual framework. More specifically, it emphasises the role of the problem statement as input information during designing.

In terms of the directionality of the design moves that resulted from each group's interactions with the problem statement, Table 5.2 provides an overview of the results.

Table 5.2: Directionality of thoughts when interacting with the problem statement

Problem statement interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	11 (3%)	11 (9.3%)	3 (1.7%)
Unidirectional backward	8 (2.2%)	13 (11%)	6 (3.5%)
Bidirectional design moves	23 (6.3%)	7 (6.7 %)	8 (4.6%)
Orphan moves	1	0	0

Table 5.2 indicates that all three groups had limited interactions with their problem statement. Group B had the most (31 interactions) of the three groups, which can be linked to their predominant involvement in problem structuring cognitive phases. On the other hand, Groups A and B barely interacted with their problem statements.

The directionality of the design moves generated by the various groups of participants show that they seldom generated bidirectional moves. Table 5.2 furthermore emphasise that participants rarely used the problem statement as a starting point for generating new thoughts, as a limited number of unidirectional forward moves occurred. In the same manner, they did not utilise the problem statement as a tool for evaluating and reflecting on already instantiated ideas.

In my attempt to understand the role of the problem statement during the participants' design processes, I also looked at the relationship between the participants' interactions with the problem statement and their addressing of design problem solving goals. The results are presented in Table 5.3.

Table 5.3: Interactions with the problem statement when attempting to achieve problem solving goals

Design problem solving goals	Group A - Problem statement interactions	Group B - Problem statement interactions	Group C - Problem statement interactions
Understanding the problem	19	5	2
Understanding context	21	24	3
Understanding materials	2	2	10
Understanding weight	0	0	1
Understanding size	0	0	0
Understanding appearance	0	0	0
Understanding shape	0	0	0
Finding a suitable solution	0	0	0
Finding suitable materials	0	0	1
Finding a suitable size	0	0	0

Finding a suitable shape	0	0	0
Committing to a solution	0	0	0
Realising solution	0	0	0
Developing committed solution	0	0	0

Table 5.3 indicates that all three groups interacted with their problem statement when trying to understand the design problem, context, and materials from which the food container had to be made. Group C furthermore interacted with their problem statement during two other design problem solving goals, namely when they were attempting to understand the weight requirements of the food container, and when searching for suitable materials. The three groups did not use the problem statement during the rest of the design problem solving goals.

These results point to the problem statement playing a small role during designing. The results can possibly be linked to the participants' disinclination to evaluate their own processes and solutions, their limited experience in design processes or the lack of training on using information in the problem statement during designing. When comparing the results I obtained to what is known, it is clear that limited literature exists on the role of the problem statement in a design education environment, more specifically in terms of interactions with the problem statement (Koronis, Silva, Kang & Chia, 2018; Sosa, Vasconcelos & Cardoso, 2018). This suggests that limited guidelines are available for professional design educators and technology teachers to guide them when preparing problem statements for design projects.

As such, the findings of the current study may inform future STEM teacher training programmes in terms of the need to teach learners how to read, analyse, frame and use information based on a problem statement. Several authors (Dorst, 2011; Goel, 1995; Roth, 1995) studying the early phases of the design process have noted the crucial role that problem framing processes may play in the design process. In addition, the problem statement does not merely serve as input information to the design process, as it can also be used as a tool for evaluating progress, productivity and quality during designing (Cross, 2008; Dym et al., 2014; Ullman, 2009). In the current study, the participants did however not do this on their own. As such, this finding points to the need for pedagogical intervention in teaching novice designer's procedural knowledge to effectively utilise a problem statement.

5.2.2 Interactions with figures

As already indicated in Table 5.1, Groups A and C had the highest number of interactions with figures during the design processes. In Excerpts 5.4 to 5.6 examples are provided of instances where and how the groups of participants interacted with figures.

P2 (move 17): We can perhaps make something like this food bag (Pointing to Figure 18)? Then you can insert something to separate the food.

P1 (move 18): Or, we can make a box and put it inside the food bag?

P1 (move 19): Then the food bag will be like an insulator

P1 (move 20): But, is this idea not a bit too expensive for someone next to the street?

P2 (move 21): Yes, well, that's why we will not be making a textile bag, but will be making a wooden box

Excerpt 5.4: Group A's interactions with figures

P2 (move 59): I think we must also use this (Pointing to Figure 16). It is telling us which materials are heat insulating.

P1 (move 60): Insulating. It stops the flow of electricity or heat.

P2 (move 61): So aluminium is the best and steel.

P3 (move 62): Ok, so what do we write? We have tinfoil, what else?

P2 (move 63): What is tinfoil here (Points to Figure 16)?

P1(move 64): Aluminium

Excerpt 5.5: Group B's interactions with figures

P1(move 58): It should be made from biodegradable materials.

P3 (move 59): Here it says compostable bowls (Pointing to Figure 10). So we can maybe do something like that and just say compostable.

Excerpt 5.6: Group C's interactions with figures

These examples provide supportive qualitative evidence for the various ways in which the groups interacted and used figures during their design processes. From Excerpt 5.4, it is for example clear that P2 in Group A used figures to initiate the group's designing of a suitable food container. He namely proposed the idea of a thermally insulated lunchbox bag after perceiving Figure 18, given as part of the STEM task, which is included here as Figure 5.5.

Figure 5.5: Figure 18 of the STEM task (thermally insulated lunchbox bag)

After P2 raised this idea, P1 proposed that they first put food into a box and then into a thermally insulated food lunchbox, based on the properties of the layers of materials, which could result in a food container being an insulator of heat. However, while looking at Figure 18, P1 commented on the economic context of the people involved, upon which P2 agreed to modifying the existing design by using cheaper materials, for instance, such as wood and cardboard to make the thermal insulated food container from.

Group B used figures in another way during their designing, as captured in Excerpt 5.5. While engaged in the problem and in searching for suitable materials to use in their design, P2 of Group B pointed to Figure 16 of the STEM task (included as Figure 5.6 here) noting that it contained useful information on the heat insulating properties of materials, which they could use.

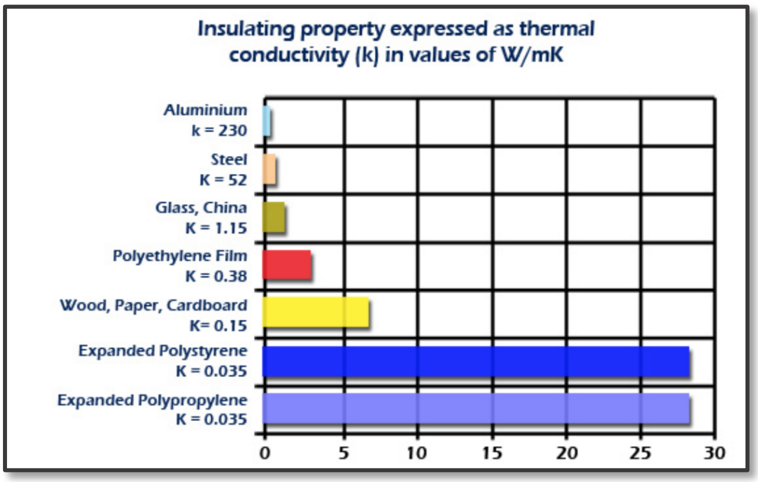
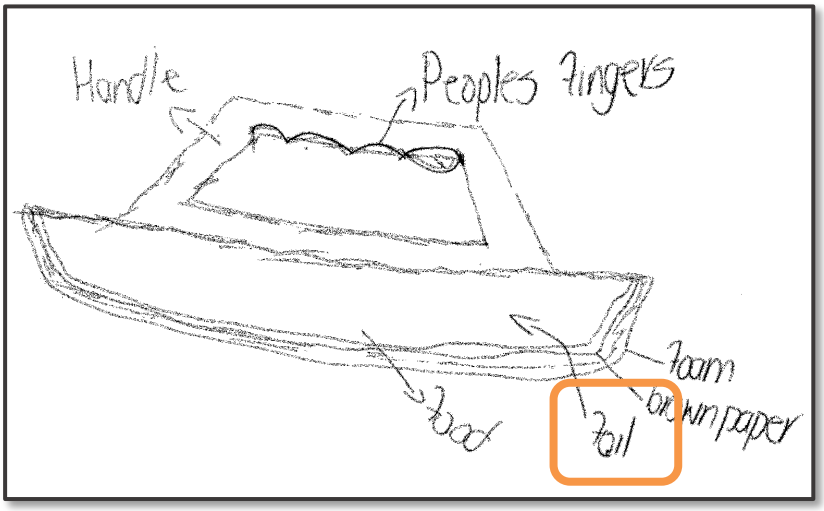


Figure 5.6: Figure 16 of the STEM task (heat insulating properties of materials)

When P2 inspected Figure 16, she noted the useful information on the heat insulating properties of materials. P1 affirmed P2's suggestion and commented that the insulating feature would imply that the flow of electricity or heat will stop. However, P2 incorrectly interpreted the graph and identified aluminium and steel as the 'best' materials for insulation. Her group members did not correct her interpretation of the graph, and instead, P3 asked what he had to add to the specification list, in addition to the aluminium foil they had selected at that time. P2 pointed to Figure 16 and asked what material 'tinfoil' is made from. P1 subsequently responded that it is the same as the aluminium in Figure 16. Group B's interaction with Figure 16 and their choice to use aluminium foil was later reiterated when they created sketches of possible solutions, as shown in Photograph 5.1.

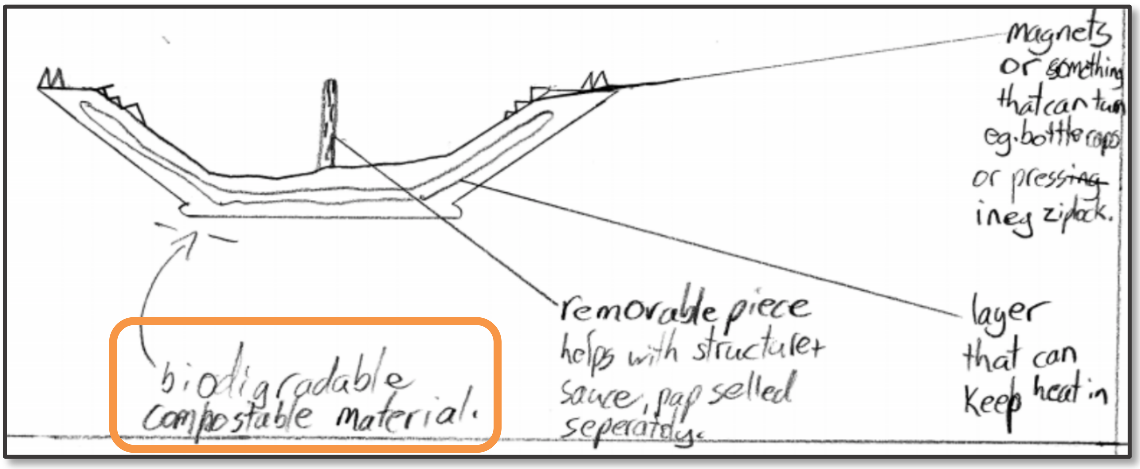


Photograph 5.1: Group B's decision to use aluminium foil in their final design

The way in which Group C interacted with a figure in solving the design problem is captured in Excerpt 5.6. During design move 58, while in the process of finding suitable materials from which they could make their food container, P1 repeated Group C's design intention to make the food container from biodegradable materials. P3 responded by pointing to the compostable bowls represented in Figure 11 of the STEM task, included here as Figure 5.7.

Figure 5.7: Figure 11 of the STEM task (compostable bowls)

By pointing everyone's attention to the picture of the compostable bowls, P3 searched for and selected information to base his design idea on. This instance represents a significant design move, which led him to include compostable materials in his final design idea, as demonstrated by Photograph 5.2.



Photograph 5.2: P3's decision to use compostable material in his final design

In summary, Excerpts 5.4 to 5.6 thus reveal some of the ways in which the participating groups interacted with visual materials during their design processes. From these excerpts, it seems clear that the participants used figures in multiple ways in finding inspiration as well as information thereby reducing some uncertainty inherent to the ill-structured nature of design problems. From an Extended Design Cognition viewpoint (Haupt, 2015), the participants' interactions with the figures can be viewed from the complementarity principle espoused by Sutton (2010) and the biological coupling principle of extended cognition theorists (Carter et al., 2018; Menary & Gillet, 2017). In this view, participants are regarded as biologically coupled with the external environment by means of direct sensory-motor interactions that can be facilitated through perception-action cycles. This means that learners can detect useful perceptual information from figures, which will result in further action, in turn feeding into further perception-action cycles.

This finding however contradicts traditional Information Processing Theories on designing Roth et al., 2017), which hold that designing will first and foremost occur in the mind of designers (Ingold, 2010; Roth et al., 2017). From this viewpoint, designers conceptualise design ideas based solely on pre-existing knowledge and experiences stored in their memory (Roth et al., 2017). Instead, this finding supports contemporary theories of designing (Haupt, 2018; Malinin, 2016; Roth et al., 2017) in which novice designers develop problem understanding and design ideas as a result of their interaction with their physical environment, by means of perception-action cycles. In order to elucidate the nature of the participants' interactions with figures during designing, Table 5.4 summarises the participants' directionality of thoughts.

Table 5.4: Directionality of thoughts when interacting with the figures provided in the design task

Figure interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	6 (1.6%)	1 (0.8%)	7 (4%)
Unidirectional backward	21 (5.8%)	3 (2.5%)	15 (8.7%)
Bidirectional design moves	94 (25.8%)	11 (9.3%)	49 (28.3%)
Orphan moves	0	1 (0.8%)	0

Table 5.4 captures the types of design moves that were generated by each group as a result of their interactions with the figures provided in the STEM task. As previously stated, Group B engaged in limited interactions with the figures during their design process. However, the interactions they did engage in with figures generated unidirectional and bidirectional thoughts. On the other hand, Groups A and C used figures extensively, in these cases as visual examples, as a means to produce thoughts that were both generative and reflective in nature.

In this study, the information represented in the figures included in the STEM task seemed to encourage the participants to copy existing ideas from perceived visual examples, *albeit* with modifications. More specifically, when comparing Groups A, B and C's final idea drawings (captured in Figure 5.8) to the figures that they used as inspiration when looking for suitable solutions, certain visual similarities between their ideas can be noted, as discussed in the section following Figure 5.8.

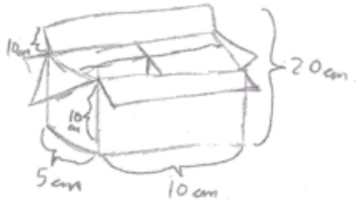
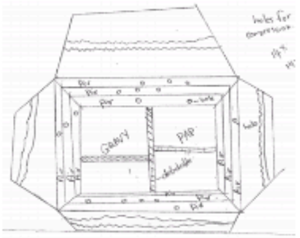
Figure	**Sketch**
Group A	
 *Figure 13*	
Group B	
 *Figure 7*	
Group C	
 *Figure 8*	

Figure 5.8: Similarities between figures in the design task and learners' final design ideas

At a first glance, it seems as if the groups merely copied their ideas from existing designs provided in the STEM task. However, upon detailed analysis of the verbal protocols, I was able to study how the participants synthesised their design ideas from various design moves that emerged during their design processes. For example, in addition to looking at Figure 13 from the STEM task, Group A generated another design idea of a foldable food container while looking at Figure 7, as shown in Figure 5.9.

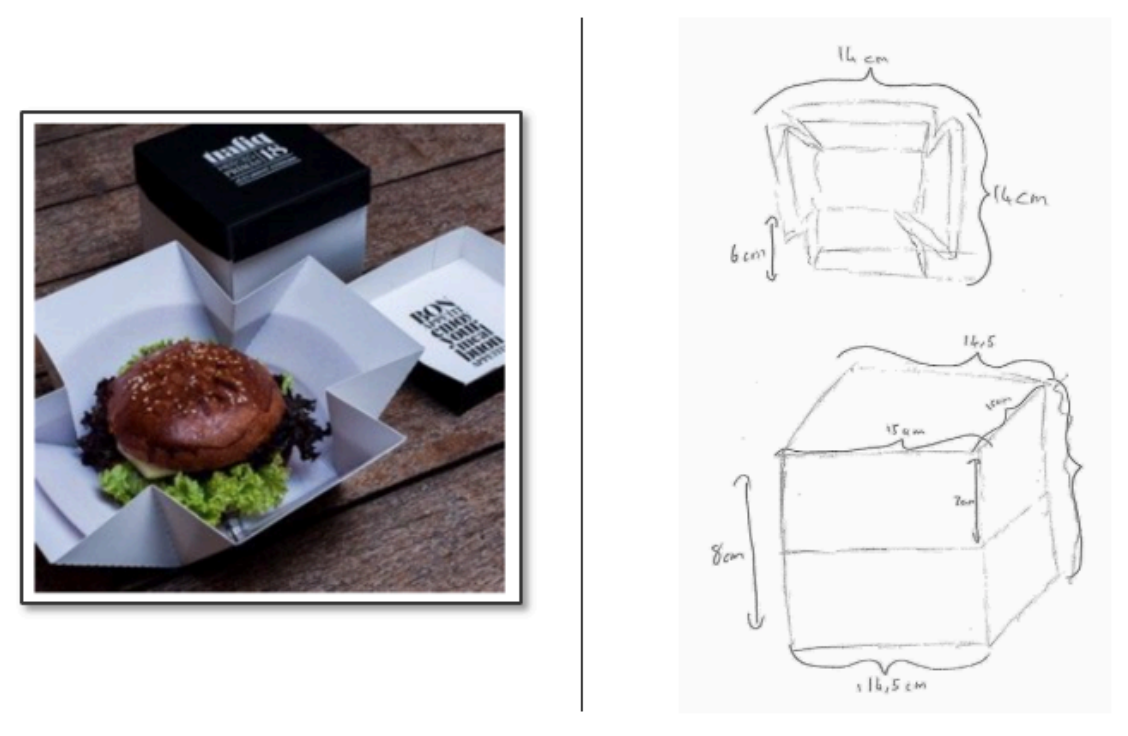
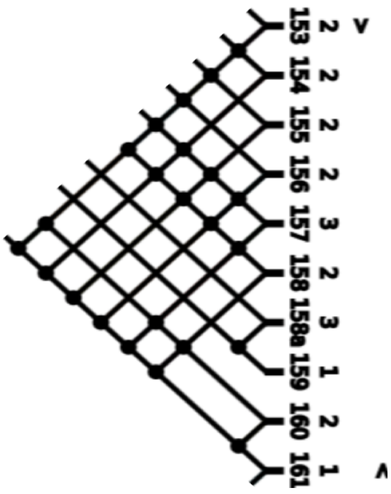


Figure 5.9: Visual example of a foldable food container and Group A's design idea

As a result of their interaction with Figure 7 in the STEM task, Group A adopted the idea of a heat retaining food container. In support of this result, the way in which Group A conceptualised their idea is captured in Excerpt 5.7, also indicating the generated linkograph.



P2: [153] Should we not try something like this (Pointing to Figure 7). We can just make it stronger and more stable
P2: [154] This can be the insulation material
P2: [155] It will be difficult to wash, but if it is recyclable, we can just recycle it
P2: [156] That can be cardboard or something stronger to resist impact
P3: [157] So it will be like a bowl with the food, and something around it all
P2: [158] Yes, so you fold it so that it would fit in there
P3: [158a] What about this idea (Pointing to Figure 12)?
P1: [159] No, it will fall out in the taxi too easily.
P2: [160] That's why you have to have a lid for the container
P1: [161] So, this idea will be our foldable container

Excerpt 5.7: Idea synthesis by Group A

When analysing the data included in Excerpt 5.7, it is clear that Group A relied on Figure 7 when designing their foldable food container. To this end, during design move 153, P2 perceived and pointed to Figure 7, proposing the idea of a foldable food container. During moves 154-156, he elaborated by proposing that the inside of the food container had to made of insulating materials, qualifying that the material had to be recyclable, and specifying that the container should be made from strong cardboard to resist external forces when being used. These elaborations can all be linked back to previous design moves that originated earlier in Group A's design process. Next, P3 and P2 further clarified their ideas by noting in design moves 157-158 that the food container could function as a bowl inside a foldable food container. This resulted in P3 identifying yet another idea while looking and pointing at Figure 12, which was included in the STEM task (shown here as Figure 5.10).

Figure 5.10: Figure 12 of the STEM task

However, P1 rejected this proposed idea based on its foreseen lack of stability in a taxi environment. In response, P2 brought the group's attention back to his foldable food container idea during design move 160, justifying his suggestion in terms of the benefit of the lid, which could for example reduce spills, when compared to P3's idea. P1 finalised the conceptualisation process by referring back to what was being discussed and confirming their new idea for development.

Studying the way in which Group A conceptualised their foldable food container points to the finding that the participants' activity of copying was not merely a mechanical routine activity. I relate this finding to Mavers's (2011, p. 15) explanation that it rather "involved a relational process where an existing material entity was interpreted and then remade as a different material entity”. In support of this, the linkograph included in Excerpt 5.7 demonstrates how the participants in Group A were able to systematically synthesise their design idea by relying on discussion and interaction with conceptual and physical information sources. This view is consistent with Extended Design Cognition Theory (Haupt, 2015), which posits that thoughts about a design object come into existence in the materiality of communication and interactions, rather than preceding it (Ingold, 2010; Jornet & Roth, 2018; Roth et al., 2017),

In the case of this study, it can thus be seen that the learners’ thoughts about their designs continued to develop and evolve as they interacted with the figures provided. Table 5.5 summarises how the participants’ interactions with figures addressed their design problem solving goals.

Table 5.5: Interactions with figures in trying to achieve design problem solving goals

Design problem solving goals	Group A – Figure interactions	Group B - Figure interactions	Group C - Figure interactions
Understanding the problem	0	0	1
Understanding context	2	0	5
Understanding materials	13	13	10
Understanding weight	1	0	0
Understanding size	0	0	0
Understanding appearance	0	0	0
Understanding shape	9	0	0
Finding a suitable solution	45	3	48
Finding suitable materials	0	0	5
Finding a suitable size	28	0	1
Finding a suitable shape	4	0	1
Committing to a solution	3	0	0
Realising solution	3	0	0
Developing committed solution	11	0	0

In summary, Table 5.5 captures data that indicate how Groups A and C used figures for the purpose of addressing their design problem solving goals. Group A predominantly interacted with the figures provided in the STEM task in finding suitable solutions and suitable sizes for their food container. They furthermore interacted with the figures to understand the different types of suitable materials and develop the solution to which they were committed. Similarly, Group C extensively interacted with the provided figures to find suitable solutions and to find the appropriate materials for their food container designs. Group B, on the contrary, did not interact much with figures, but when they did, they primarily used it to find suitable materials for their design.

Research on professional designers indicates that the exposure of designers to visual examples during idea generation may have positive and negative consequences for design performance (Gonçalves et al., 2014; Perttula & Liikkanen, 2010; Vasconcelos et al., 2016), with both creative as well as mundane outcomes (Vasconcelos et al., 2016). In the case of my study, the novice designers demonstrated fixation behaviour (Nicholl & Mclellan, 2005; Vasconcelos et al., 2016) which is typically observed when visual examples are given to learners during idea generation. As such, this study supports previous studies in which learners demonstrated fixation as a result of their interaction with visual examples (McLellan & Nicholl, 2011; Nicholl & Mclellan, 2005).

5.2.3 Interactions with drawings and written notes

In addition to interacting with figures when solving their design tasks, the various groups also relied on drawings and written notes – to various degrees. As an example, the way in which Group A interacted with drawings in order to develop their chosen design idea is captured in Excerpt 5.8. Due to the fact that the participants of the various groups engaged in similar interactions with the drawings, I only include Group A as example excerpt in this section.

P2: (move 69) We almost want to do it like a house… (Starts sketching)

P3: (move 70) Like this house (pointing to Figure 15)?

P2: (move 71) Yes, something like that. We can just make it stronger?

P1: (move 72) Like this (pointing to Figure 8)?

P2: (move 73) Yes, something like that, we just need to reinforce it with rubber or plastic. That would do the job.

P3: (move 75) Then we draw in something like this (sketches the separator)

P2: (move 79) And then we can divide this into half, or divide it into four

Excerpt 5.8: Group A's interactions with drawings

Excerpt 5.8 reveals how Group A used their drawings to conceptualise their final design idea. Prior to the instantiation of move 69, the participants were engaging in a problem structuring cognitive phase, trying to understand and consider suitable materials to manufacture a fit-for-purpose food packaging design. During move 69, P2 proceeded to a problem solving cognitive phase when he proposed and sketched a design idea in the shape of a house, as captured in Photograph 5.3.

Photograph 5.3: Sketch illustrating a design idea (Group A)

Looking at this sketch, P3 and P1 qualified the design idea during design moves 70 and 72 when respectively pointing to the visual examples included as Figure 5.11 (Figures 15 and 9 of the STEM task).

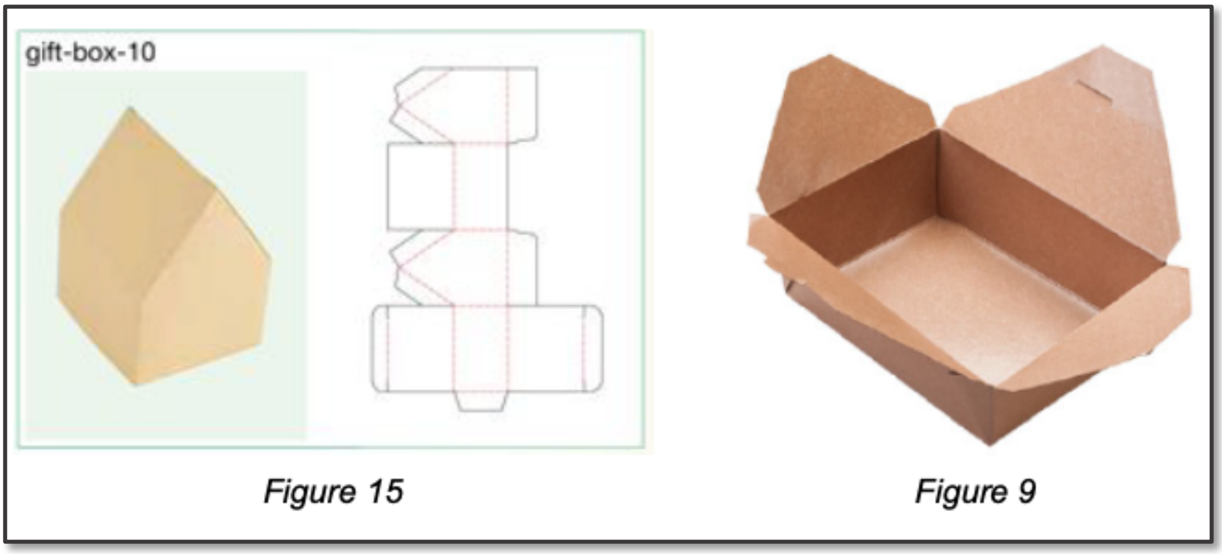
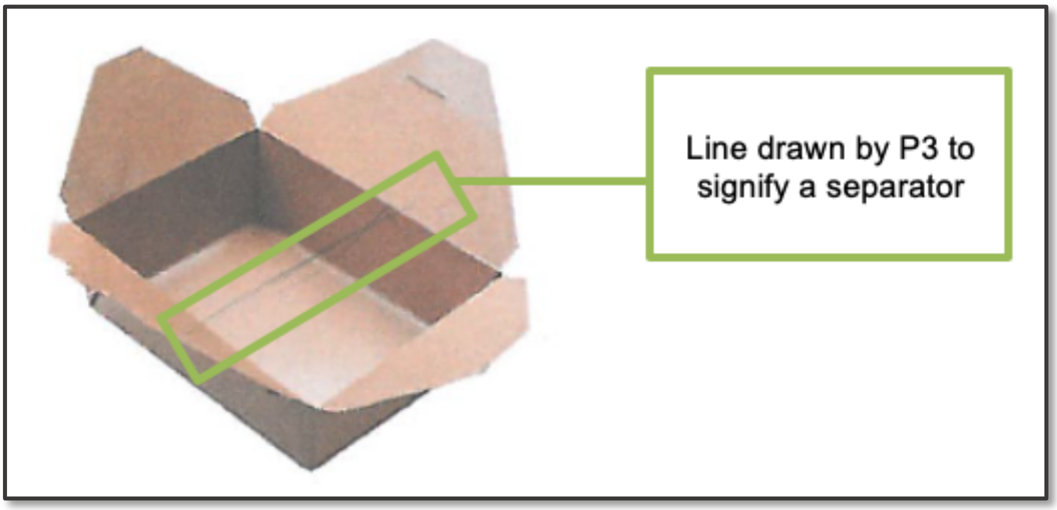


Figure 15

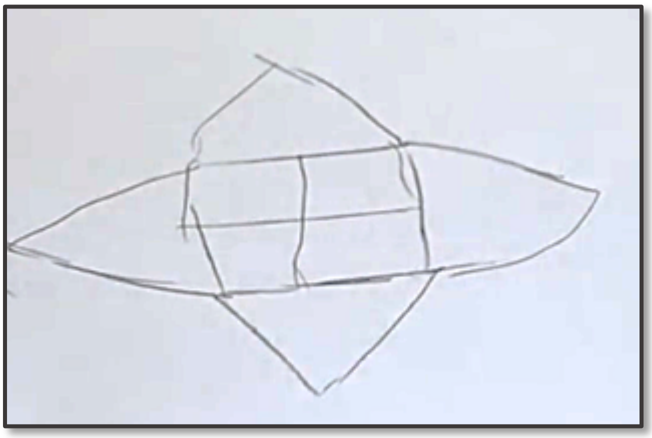
Figure 9

Figure 5.11: Visual examples noted by P1 and P3

Based on these visual examples, P2 elaborated on his initial idea and indicated that they had to strengthen their design idea by, for example, using plastic or rubber – both materials that had been mentioned earlier in the design process. During move 75, whilst looking at Figure 9, P3 elaborated, stating that they could separate the food in the container, when he drew a line, signifying a separator applied to Figure 9, as shown in Photograph 5.4. P2 subsequently re-drew their idea in another sketch during design move 79 to show this elaboration. This action is captured in Photograph 5.5 below.


Line drawn by P3 to signify a separator

Photograph 5.4: Adapting Figure 8 to indicate a separator for the design idea



Photograph 5.5: Reinterpretation of P3’s design idea

As such, Photograph 5.5 illustrates P2’s reinterpretation of P3’s addition of a separator element to their initial design idea. P2 furthermore voiced the possibility of the separator being used for two or four compartments. As with their interactions with the other physical structures, the participants’ interactions with their drawings can also be described in terms of the directionality of thoughts that were produced. Table 5.6 provides an overview of the different types of thoughts that were generated by each group of participants as a result of their interactions with their drawings.

Table 5.6: Directionality of thoughts when interacting with drawings

Drawing interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	2 (1.7%)	2 (1.2%)
Unidirectional backward	19 (5.2%)	8 (6.8%)	12 (6.9%)
Bidirectional design moves	42 (11.3%)	4 (3.4%)	46 (26.6%)
Orphan moves	0	0	0

The data captured in Table 5.6 indicate that Group B strongly relied on their drawings for evaluative or reflective purposes, while Groups A and C were able to generate bidirectional design moves when interacting with drawings. Group B was however mostly engaged in problem structuring cognitive phases, most probably resulting in the lack of bidirectional design moves. Across the groups, sketches seemingly enabled the participants to record previously generated thoughts while modifying and building on these. The participants' interactions with sketches are further presented in more detail in Table 5.7.

Table 5.7: Interactions with drawings when trying to achieve design problem solving goals

Design problem solving goals	Group A – Drawing interactions	Group B - Drawing interactions	Group C - Drawing interactions
Understanding the problem	1	0	0
Understanding context	0	0	2
Understanding materials	0	0	5
Understanding weight	0	0	0
Understanding size	0	0	0
Understanding appearance	0	0	0
Understanding shape	0	0	0
Finding a suitable solution	14	13	42
Finding suitable materials	0	0	1
Finding a suitable size	22	0	8
Finding a suitable shape	6	0	2
Committing to a solution	0	0	0
Realising solution	0	0	0
Developing committed solution	18	0	0

In looking at the number of interactions that the groups of participants had with drawings when attempting to achieve various problem solving goals, all three groups used sketches when finding suitable solutions during designing. Even though Group B only interacted with their sketches when finding suitable solutions, Group A extensively interacted with drawings in choosing suitable solution concepts and during the process of developing these concepts. During this development, participants in Group A specifically focused on finding suitable sizes for each of their solution concepts. Finally, Group C interacted with their sketches when working towards achieving various problem solving goals, such as understanding the context and materials required during the problem structuring cognitive phases, as well as finding suitable materials, sizes and shapes for their designs during the problem solving cognitive phases.

The findings related to the participants' use of drawings contradicts a previous study (Welch et al., 2000), in which it was found that learners will seldom use sketches during the early phases of the design process, as they prefer to use 3D modelling instead. In my study, I found that both Groups A and C extensively used sketches to generate and find possible solutions to their design problems. This incongruent finding may perhaps be attributed to the nature of the given design problem, as proposed by Goldschmidt and Smolkov (2004). In addition, factors such as the participants' levels of visualisation skills, as well as their (perhaps limited) confidence in using sketching or design task instructions may explain this contradiction. Further research is however required to understand under which conditions learners will engage in sketching behaviour, in order to come to a conclusive finding.

In terms of the groups' use of written notes, I obtained limited data. As Groups A and B occasionally pointed to their notes during the protocols without making utterances, I was unable to capture extensive data in terms of their use (or not) of written notes. Table 5.8 however summarises the participants' thought directionality in terms of the written notes they did create.

Table 5.8: Directionality of thoughts when interacting with written notes

Written note interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	0	0
Unidirectional backward	16 (4.3%)	0	0
Bidirectional design moves	27 (7.4%)	5 (4.2%)	0
Orphan moves	0	0	0

In contrast with Groups B and C, Table 5.8 provides evidence on Group A's interactions with their written notes, generating both unidirectional backward and bidirectional design moves. This implies that the participants did not only use their own written notes to reflect on, evaluate or summarise previously generated thoughts in the case of the unidirectional backward design moves, but also generated new thoughts that may be linked to subsequent thoughts. Group B engaged in limited interactions, which generated only five bidirectional design moves with their written notes, while Group C did not use any written notes during their design process.

In analysing the interactions with written notes in more detail (refer to Table 5.9), it is evident that Group A used written notes most often when attempting to find suitable sizes for their designs and while developing the solution to which they committed as their final design idea. They also used their written notes during problem structuring cognitive phases, in attempting to understand the problem, materials and their shapes. Group B, who had limited interactions with their written notes, similarly used these during the problem structuring cognitive phase when they were attempting to understand the problem and possible materials for their design solution. They also used written notes during the problem solving cognitive phase when searching for a suitable solution. Group C did not have any interactions with their written notes.

From an Extended Design Cognition perspective, the participants of this study mainly used written notes as part of their epistemic practices (Menary & Gillet, 2017). In this way, they used written notes to simplify cognitive processing, for example, remembering a range of material options for manufacturing, while also eliminating non-biodegradable ones. As such, the participants were able to augment their cognitive processing of remembering as proposed by Menary and Gillet (2017).

Table 5.9: Interactions with written notes when trying to achieve design problem solving goals

Design problem solving goals	Group A – written note interactions	Group B - written note interactions	Group C - written note interactions
Understanding the problem	1	1	0
Understanding context	0	0	0
Understanding materials	6	1	0
Understanding weight	0	0	0
Understanding size	0	0	0
Understanding appearance	0	0	0

Understanding shape	1	0	0
Finding a suitable solution	0	3	0
Finding suitable materials	0	0	0
Finding a suitable size	22	0	0
Finding a suitable shape	1	0	0
Committing to a solution	0	0	0
Realising solution	0	0	0
Developing committed solution	12	0	0

5.2.4 Interactions with physical objects and tools

Next, the various groups of participants were found to also interact with physical objects and tools during the STEM task. The following excerpts provides supportive evidence for the manner in which Groups A and B interacted with objects and tools simultaneously when engaging in both the problem structuring and problem solving cognitive phases. Excerpt 5.9 encompasses Group A’s discussions regarding the weight that the container needed to carry and their subsequent use of a kitchen scale to determine its dimensions and weight bearing.

P2: (move 309) Will the container be able to hold 1.1kg? Is the container not too small? It will have to be a bit wider I think (pointing to the writing).

P1: (move 310) What is 1kg? How much will 1kg be?

P3: (move 311) I think it will be about five of these cool drink cans?

P2: (move 312) How full is the can? How many milliliters do you estimate?

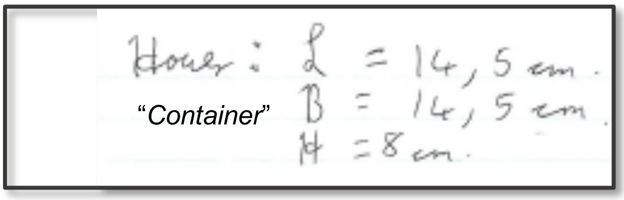
P1: (move 313) It is about .. 200ml

P3: (move 314) So, a kilogram.... a liter is a kilogram…

P3: (move 315) Let’s weigh it (uses kitchen scale). 500... Ok, so it needs to carry 2 of these bottles

Excerpt 5.9: Group A’s interaction with physical objects and tools

Prior to design move 309, Group A was in the process of determining the size of their design idea. During design move 309, while looking at the dimensions of their food container (captured in Photograph 5.6), P2 paid attention to the weight requirement in the problem statement, requiring of the container to be suitable to carry 1.1 kilograms. Considering this weight requirement, P2 then evaluated whether or not their design, based on the specified size they wrote in the specification list, would be able to hold 1.1 kilograms.



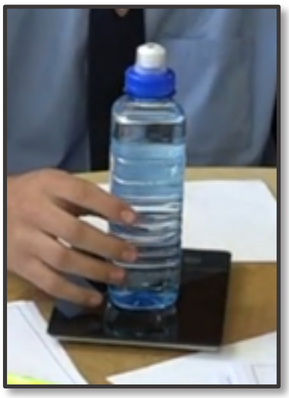
Houer: L = 14,5 cm.
"Container" B = 14,5 cm
H = 8 cm.

Photograph 5.6: Group A's specifications for their design idea

After P2 noted the written dimensions, P1 asked the rest of Group A how much 1.1 kilograms are. This question prompted P3 to ask for a kitchen scale and measure his cold drink can with some liquid in it, as captured in Photograph 5.7.

Photograph 5.7: Determining the weight of a cold drink can containing some liquid

As a result, P3 determined the weight of the can of cold drink as 200 grams, and then suggested that 1.1 kilograms should in other words be made up of five such cans. P2 asked P3 about the cold drink left in the can and P3 estimated this to be about 200 millilitres. This estimation resulted in P3 assuming that one kilogram could be compared to about one litre. Testing his assumption, he weighed a full 500 millilitres water bottle, as shown in Photograph 5.8.



Photograph 5.8: Measuring the weight of a full 500 millilitre water bottle

P3 was subsequently able to affirm his assumption that one litre would be equal to one kilogram. He next stated that the food container thus needed to be able to carry two such water bottles, addressing P1's question in move 310 pertaining to the 1.1 kilograms. During move 321, the participants measured the length and height of the water bottle using a ruler (refer to Photograph 5.9), and decided that their initial dimensions were sufficient to carry 1.1 kilograms.

Photograph 5.9: Measuring the length of a 500 millilitre water bottle

By measuring the water bottle's dimensions, Group A was thus able to verify their proposed dimensions for their food container design. As such, the way in which Group A interacted with tools and physical objects contributed to their development of the design specification. Their interaction with the tools and physical objects more specifically transformed their abstract representation of size into a physical understanding of 1.1 kilograms, and the relevance thereof to the weight requirement of the food container.

In support of this example, Group B similarly interacted with measurement tools and physical objects in order to develop the size specifications for their design. Excerpt 5.10 provides the necessary background.

P3: (move124) We can measure this (foil container)

P2: (move 125) With the ruler.

P2: (move 126) Which one do you want to use?

P3: (move 127) This one or this one?

P2: (move 128) I think this one (Deeper foil container)

P2: (move 129) This one? (Deep container)

P1: (move 130) No that one (points to shallow foil container)

P1: (move 135) Twenty, twenty, twenty…. Two hundred and thirty millimetres.

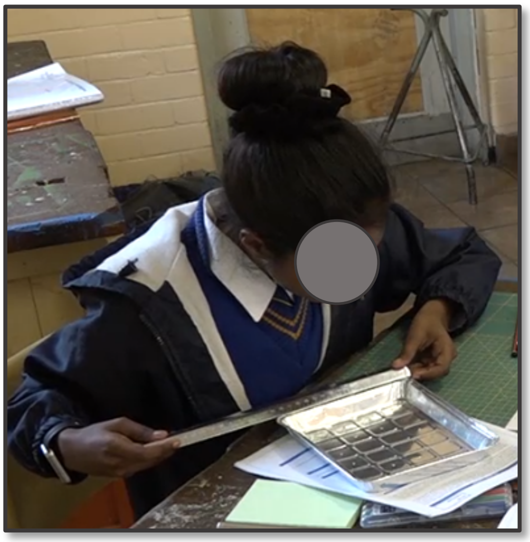
P1: (move 138) One sixty… One hundred and sixty five millimetres

Excerpt 5.10: Group B's interaction with physical objects and tools

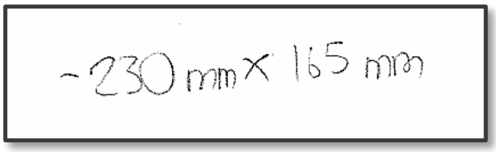
As captured in Excerpt 5.10, Group B was reading from the instructions in order to formulate their specification list prior to the instantiation of design move 124. This prompted them to consider the dimensions of their food container. During move 124, P3 to this end suggested that they measure existing aluminium foil containers as a strategy to determine the size of their design. However, since more than one size of these containers were available to them, they had to make a choice between two different sizes, as illustrated in Photograph 5.10.

Photograph 5.10: Deciding which container to measure

Photograph 5.10 thus shows the instance during move 127 when P3 raised two different sizes of aluminium foil containers from which the group had to decide which one to use in order to determine the size of their design. P2 and P3 differed in opinion on which one of the two containers to choose, as captured in design moves 128, and 130, with P2 choosing a deep container and P3 a shallow container. In the end, they selected the shallow container during move 130 and started to measure it by using a ruler in design move 135, as captured in Photograph 5.11. The dimensions were uttered by P1 during design moves 135 and 138, after which P3 recorded the dimensions in the specification list, as depicted in Photograph 5.12.



Photograph 5.11: Measuring the breadth and length of the selected foil container



-230 mm × 165 mm

Photograph 5.12: Measurements of the tinfoil container that was recorded by P3 in the specification list

During this phase of the design process, the participants therefore utilised an aluminium foil container as model for their own design's dimensions. They did not explain why they chose the specific container, or how it relates to the design requirements. However, this process apparently provided them with a means to concretise the abstract idea of size into a measurable unit.

Both Groups A and B's interactions with physical objects confirm and illustrate the Ecological Psychology principle of intention-attention (Young, 2004) that is embedded in the Extended Design Cognition Theory (Haupt, 2015). According to Young (2004), intentional dynamics will play a valuable role during design problem solving as it will generally harness learners' perceptual systems to detect functional information in the physical environment that can be acted upon in order to address a design intention.

In both Group A and B's cases, the participants were guided by their intentional dynamics to determine the weight requirement of the food container (Group A), or to find a suitable size for the food container (Group B). For both groups, these intentional dynamics gave purpose and guided their perception-action cycles to detect functional information in the environment. In the case of Group A, the participants had the intention to determine the weight requirement for the food container. Their attention was subsequently attuned to environmental information sources, including a kitchen scale, cold drink can, bottle of water and a ruler, which could help them determining the weight requirement. Similarly, Group B wanted to find a suitable size for their food container, resulting in their intentions being attuned to aluminium foil containers and a ruler.

The way in which designers' thoughts developed as a result of their interactions with physical objects as well as their attempts to address their problem solving goals is summarised in Table 5.10 and 5.11.

Table 5.10: Directionality of thoughts when interacting with physical objects

Physical object interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	7 (5.9%)	2 (1.2%)
Unidirectional backward	3 (0.8%)	18 (15.3%)	3 (1.7%)
Bidirectional design moves	12 (3.3%)	18 (15.3%)	6 (3.5%)
Orphan moves	0	2 (1.7%)	0

From Table 5.10 it can be deduced that all three groups interacted with physical objects (even though to a limited extent) during their design processes. These interactions led to productive design moves for all three groups. Even though Group B did not significantly use sketches or figures when compared to Groups A and C, they used physical objects in an extensive way, as environmental scaffolds. These interactions with physical objects resulted in Group B producing unidirectional forward and backward moves, bidirectional moves and orphan moves. This trend in turn contributed to their thought development during the designing process. On the contrary, Group A's interactions with physical objects did not result in unidirectional forward moves. This implies that the participants did not use physical objects as stimuli to generate new thoughts or ideas without connecting these two preceding thoughts. Group C, on the other hand, had limited interactions with physical objects and relied on figures instead.

Table 5.11: Groups A, B and C's interactions with physical objects when trying to achieve design problem solving goals

Design problem solving goals	**Group A – physical object interactions**	**Group B - physical object interactions**	**Group C - physical object interactions**
Understanding the problem	0	0	0
Understanding context	0	0	0
Understanding materials	2	0	2
Understanding weight	4	0	0

Understanding size	0	0	0
Understanding appearance	0	1	0
Understanding shape	0	0	0
Finding a suitable solution	3	16	8
Finding suitable materials	0	20	0
Finding a suitable size	3	8	1
Finding a suitable shape	3	0	0
Committing to a solution	0	0	0
Realising solution	0	0	0
Developing committed solution	0	0	0

In analysing the data captured in Table 5.11, it can be seen that the participants did not extensively interact with any specific physical objects. Group A interacted with physical objects during problem structuring phases when attempting to understand and find suitable materials and sizes. They also interacted with physical objects for problem solving when looking for and finding suitable solutions, shapes and sizes. Likewise, Group B primarily used physical objects when trying to find suitable solutions, materials and sizes. Group C mostly used physical objects when searching for suitable solutions.

The findings I obtained corresponds with the principles of Extended Design Cognition Theory, which indicate that physical objects in participants' design task environments afford opportunities for action (Haupt, 2015). When the participants in this study interacted with physical objects, they were accordingly able to, achieve their problem solving goals. This finding furthermore suggests that, for design education, the role of the design task environment can provide environmental cues for realising learners' design intentions.

In a similar way that learners interacted with physical objects, they also interacted with tools. The participants' directionality of thoughts when interacting with tools, as well as how they were able to achieve each of their design goals, is presented in Tables 5.12

and 5.13. These interactions with tools can be regarded as significant as it allowed the participants to find suitable sizes for their designs.

Table 5.12: Directionality of thoughts when interacting with tools

Tool interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	0	0
Unidirectional backward	8 (2.2%)	2 (1.7%)	1 (0.6%)
Bidirectional design moves	40 (11%)	1 (0.8%)	10 (5.8%)
Orphan moves	0	0	0

Table 5.12 indicates that the participants' interactions with tools did not produce any unidirectional forward design moves. Group A however used tools when producing unidirectional backward moves. This was possibly due to their 'guess and test' strategy when estimating sizes. To this end, they would guess the required sizing, where after they confirmed this with actual measurements using a ruler as tool. The spike in frequency of Group A's interaction with tools, as seen in their bidirectional design moves, can probably be ascribed to their attempt to find suitable sizes for their design solutions. While Group B interacted with tools to a limited extent, Group C generated some bidirectional moves as a result of their interactions with tools.

In terms of the design problem solving goals, the data in Table 5.13 reveal that the majority of Groups A and C's interactions occurred when they were attempting to find suitable sizes for their design ideas, as indicated earlier. It can be seen that they rarely interacted with tools in achieving their design goals. However, this may be attributed to the instructions in the problem statement, which indicated that the groups had to determine the size of the object they were to design. This further implies that they used the available tools for this purpose and this purpose only.

Table 5.13: Interactions with tools when trying to achieve design problem solving goals

Design problem solving goals	Group A – tool interactions	Group B - tool interactions	Group C - tool interactions
Understanding the problem	0	0	0
Understanding context	0	0	0
Understanding materials	0	0	0
Understanding weight	3	0	0
Understanding size	0	1	1
Understanding appearance	0	0	0
Understanding shape	0	0	0
Finding a suitable solution	0	2	0
Finding suitable materials	0	0	0
Finding a suitable size	45	0	10
Finding a suitable shape	0	0	0
Committing to a solution	0	0	0
Realising solution	0	0	0
Developing committed solution	0	0	0

The way in which the participants interacted with tools can be described through an Activity Systems Theory lens (Engeström, 2015) and in particular through the principle of tool mediation (Kaptelinin & Nardi, 2006; Vygotsky, 1978). In this regard, tools seemingly mediated the subjects in Groups A and B's behaviour for realising their objects (intentions). The nature of the tools that the participants engaged in contained culturally embodied knowledge, which specified affordances that the participants could act upon to realise their intentions (Stevenson, 2004). Although tools are prominent in any design task environment, the role of tools have not been researched widely in design education environments, as these environments often lack a range of physical tools (Hmelo et al., 2000; Shaffer & Clinton, 2006; Slangen et al., 2011). Furthermore, the exact nature of student learning that takes place during interactions with tools often remain ambiguous, resulting in a need for ongoing research.

5.2.5 Interactions with textbooks

In Excerpts 5.11 and 5.12 I provide examples of Groups A and B's interaction with their textbooks, even though this was found to be minimal. Group B namely used their textbook during problem structuring in gaining a better understanding of the terms used in the problem statement, while Group A were initially searching for biodegradable material examples in their textbook, but did not succeed in the search

P3: (move 44) We are looking for something that is biodegradable and that can insulate

P1: (move 45) Lets look at this for a bit (starts to read from class notes). "The design process, what is it? Investigate... describe the situation"

Excerpt 5.11: Group A's interaction with class notes

P3: (move 54) (Reading instruction from problem statement) "Write a design brief, a specification and the constraints for your design solutions". So we start by design brief right?

P1: (move 55) Ok, Im gonna use the textbook.

P3: (move 54) Ok, design brief why don't we like we say, we are gonna start off with like a simple container sort of like a foil container.

P3: (move 57) It's a design brief, it's our actual design. So, take out all the parts that we are using in our design and write them in the form of a paragraph.

P3: (move 84) No I think I made a mistake. Design brief shouldn't be a list of parts, it should be the reason why we're designing and building it then.

P3: (move 85) Oh design brief. (reads form textbook glossary) "a short and clear statement that gives the general outline of the problem to be solved as well as the purpose of the proposed solution." So we are not there we still have to talk about WHY we build it.

P1: (move 86) Ok so basically the purpose

Excerpt 5.12: Group B's interaction with a textbook

In the case of Group A, during design move 44, the participants were in the process of investigating insulating materials that are biodegradable, when reaching an impasse. This prompted P1 to start reading from their class notes on the nature of the design process. As shown in Figure 5.12, this resulted in an orphan design move that was not connected to any past or future design moves, as the information was not relevant to finding biodegradable insulation materials.

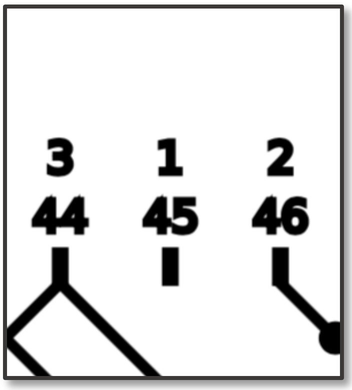


Figure 5.12: Orphan move generated as a result of interaction with the textbook

In the case of Group B, the participants seemingly benefited from their interactions with the textbook on one occasion. Upon reading one of the instructions from the problem statement to write a design brief, P1 responded that she could use the textbook to help them with the task. P3, however, did not pay attention to her statement, and started to describe a vision for their design idea during move 54. During move 57, P3 started to deliberate the meaning of a design brief, saying that it should contain the different parts of the design object. However, during move 84, when writing the design brief, P3 started to correct himself by saying that he had made a mistake during design move 57. It was at this point (move 58) where he started reading from the textbook glossary to discover the meaning of a design brief. Subsequently, P3 and P1 realised that a design brief should provide the reason and purpose for designing an artefact, in this case thus a food container. In summary, Excerpts 5.11 and 5.12 point to the finding on the use of textbooks not significantly helping the participants, for the most part in completing their design processes. Even though Group B used their textbook, this was rudimentary as they were merely utilising it to better understand the terminology used in the problem statement, i.e. ‘design brief’.

In Table 5.14, I summarise the learners’ directionality of thought when interacting with textbooks and class notes.

Table 5.14: Directionality of thoughts when interacting with textbooks and class notes

Textbook interactions			
	Group A	Group B	Group C
Unidirectional forward	0	0	0
Unidirectional backward	0	2 (1.7%)	0
Bidirectional design moves	0	1 (0.8%)	0
Orphan moves	1 (0.3%)	0	0

The data in Table 5.14 confirm that the groups had limited interactions with their textbooks and class notes. Group B, who of the three groups had the most interactions with their textbook, only generated three design moves, for this purpose, including two unidirectional backward moves and one bidirectional move. A possible reason for the groups' limited interaction with their textbooks may relate to the perceived irrelevance of information for the specific design task that was given to the participants. In order to understand the nature of the four interactions with class notes and textbooks, Table 5.15 summarises the participants' use of textbooks and class notes in relation to them trying to achieve their problem solving goals.

Table 5.15: Interactions with textbooks or class notes when trying to achieve design problem solving goals

Design problem solving goals	Group A – textbook interactions	Group B - textbook interactions	Group C - textbook interactions
Understanding the problem	0	3	0
Understanding context	0	0	0
Understanding materials	1	0	0
Understanding weight	0	0	0
Understanding size	0	0	0
Understanding appearance	0	0	0
Understanding shape	0	0	0
Finding a suitable solution	0	0	0

Finding suitable materials	0	0	0
Finding a suitable size	0	0	0
Finding a suitable shape	0	0	0
Committing to a solution	0	0	0
Realising solution	0	0	0
Developing committed solution	0	0	0

The data in Table 5.15 indicate the occurrences of Group A and B’s interactions with their textbooks for the purpose of achieving their problem solving goals. Group A produced an orphan move while reading from the textbook on the nature of materials, while Group B produced design moves when consulting the textbook in an attempt to understand the problem they needed to solve. In their case, they were trying to understand what was meant by the concept ‘design brief’.

Overall, the participants, had hardly had any interactions with their textbooks during designing. A reason for this finding might be linked to technology teachers not often contextualising textbook content for learners’ design projects (Ramaligela, Gaigher & Hattingh, 2014). As textbooks in South Africa are compulsory, it might be worthwhile to investigate the usefulness of textbooks for novice designers, more specifically in terms of the type of scaffolds and information that is required to support effective design processes. From an Ecological Psychology perspective, learners will detect and use functional information with specific opportunities for action to complete cognitive tasks (Young, 2004). In this regard, teachers may consider ways of emphasising the functional value of information when facilitating thinking during designing. However, this idea requires further investigation before reaching a conclusion.

5.2.6 Interactions with 3D models

Interacting with 3D models enabled the participants of Group A to obtain a better idea of the separator element that they wanted to incorporate in their design, as well as to model their potential design idea. Excerpt 5.13 captures the essence hereof.

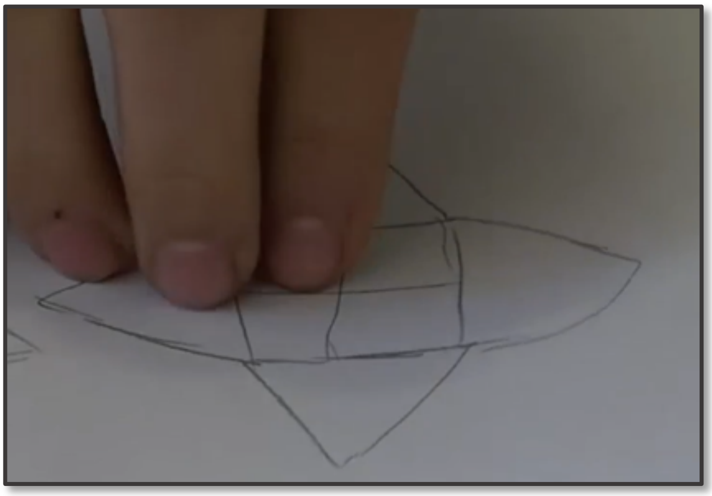
P1: (move 80) We can make this (points to drawing) so that it can come out

P3: (move 81) Oh, so that if you want to mix it (the pap and the meat)

P1: (move 84) If you cut the paper here, then you take another paper and move it into this slit and take it out like this

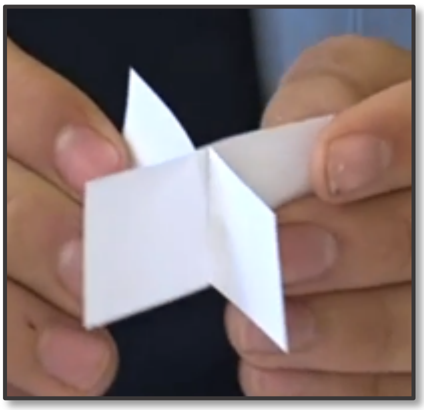
Excerpt 5.13: Group A's interaction with 3D modelling materials

Excerpt 5.13 thus captures the moment where Group A discussed the use of a separator element in their design idea. While discussing their goal to incorporate a separator element into their design idea, P1 pointed to their drawing in order to elaborate on the idea of a separator, as captured in Photograph 5.13.



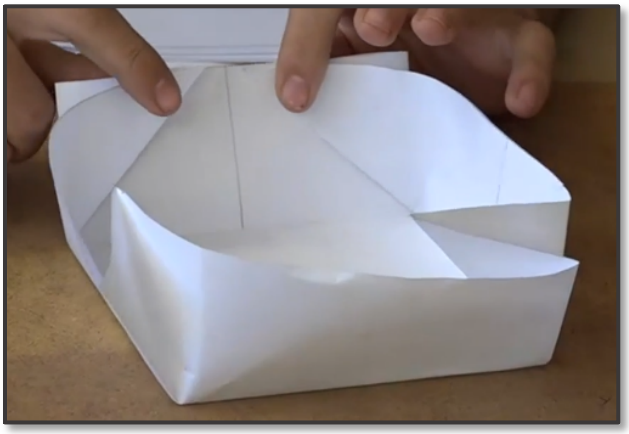
Photograph 5.13: Pointing to the separator element in the design drawing

After P1 pointed to the separator element in the design drawing, P3 motivated his suggestion that the separator element could potentially be adjustable for users who wanted to mix their pap and meat when eating. During move 84, P1 started modelling his idea for the separator by using a paper and scissors to illustrate the proposed separator's working principle. The model P1 subsequently made is shown in Photograph 5.14. As a result of the 3D modelling P1 completed, Group A was able to gain a better understanding of the separator element that they were planning to incorporate in their design idea to separate the pap and the meat.



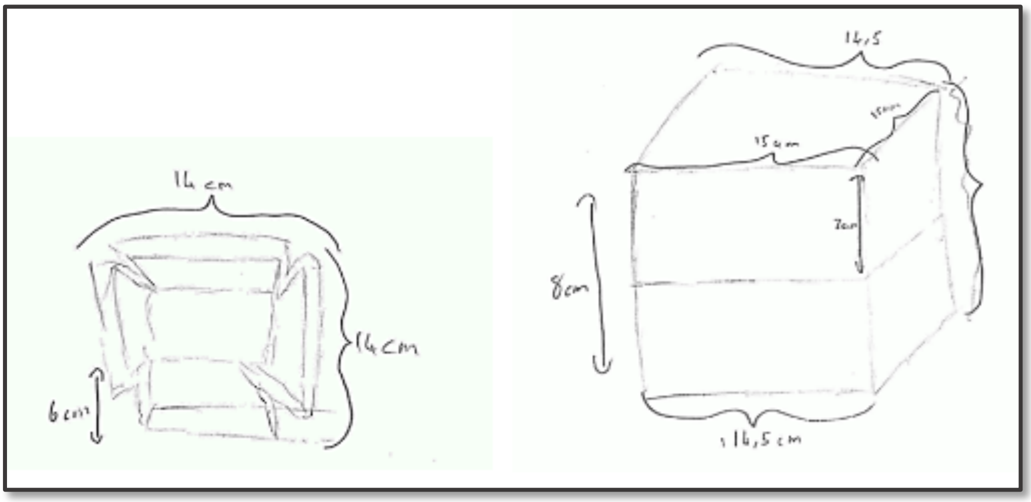
Photograph 5.14: 3D model of the separator element

During a different design idea development instance, Group A made another 3D model to understand the working principle of a foldable plate container that they perceived from Figure 7 (previously discussed in Figure 5.9). Their 3D model is provided in Photograph 5.15.



Photograph 5.15: 3D model of the foldable food container

This 3D modelling process was fundamental for Group A, as they used the model to determine whether or not the design idea would be feasible. In addition, they relied upon their 3D model to finally record the dimensions of their design idea as captured in Photograph 5.16. As such, Group A's conceptualisation of the foldable design idea involved bidirectional thoughts as the participants accessed previous thoughts when perceiving the idea from Figure 7 in the STEM task to generate new thoughts during the 3D modelling, which concluded later during their sketching episode.



Photograph 5.16: Foldable plate design drawings with dimensions indicated

The way in which Group A's 3D modelling influenced the development of their thought processes is captured in Table 5.16, in terms of their thought directionality.

Table 5.16: Directionality of thoughts when interacting with 3D models

3D model interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	1 (0.3%)	0	0
Unidirectional backward	6 (1.6%)	0	0
Bidirectional design moves	23 (6.3%)	0	0
Orphan moves	0	0	0

The data captured in Table 5.16 reveals that only Group A produced design moves while interacting with the 3D models that they made during their design process. Furthermore, their interactions with the 3D models contributed to the productivity of their thought process as it generated 23 bidirectional design moves, six unidirectional backward design moves, and one unidirectional forward move. The produced bidirectional moves indicate that Group A's production of 3D models seemingly enabled them to refer back to previously generated thoughts while being able to modify and build on these by adjusting their models. The participants' interaction with the 3D models in achieving their problem solving goals, is presented in Table 5.17.

Table 5.17: Interactions with 3D models when trying to achieve design problem solving goals

Design problem solving goals	Group A – 3D model interactions	Group B - 3D model interactions	Group C - 3D model interactions
Understanding the problem	0	0	0
Understanding context	0	0	0
Understanding materials	0	0	0
Understanding weight	0	0	0
Understanding size	0	0	0
Understanding appearance	0	0	0
Understanding shape	0	0	0
Finding a suitable solution	4	0	0
Finding suitable materials	0	0	0
Finding a suitable size	8	0	0
Finding a suitable shape	0	0	0
Committing to a solution	0	0	0
Realising solution	14	0	0
Developing committed solution	0	0	0

As indicated in Table 5.17, Group A predominantly made use of 3D models during their problem solving cognitive phases when attempting to find suitable solutions and sizes, and when realising their selected solution concept. As discussed in the previous sections, Groups B and C on the other hand preferred to use sketches to model their design ideas in spite of having access to a range of modelling materials.

Excerpt 5.13, Photographs 5.13 to 5.16 and Tables 5.16 and 5.17 therefore provide evidence of Group A's thought processes while making a 3D model of their design idea. Their modelling behaviour corresponds to Clark's (2008, p. 281) view that, during cognitive activities such as sketching or modelling, a "criss-cross brain, body and world process" is followed. In this regard, the participants engaged in multiple perception-action cycles in which they perceived information from their sketches and figures, in order to make a 3D model of a foldable food container. This demonstrates the application of contemporary Extended Design Cognition theories, which state that the act of bringing thoughts into material form, is not merely to make thoughts visible, but also constitutive of the creative activity (Heersmink, 2017; Roth et al., 2017). In this regard, Group A’s cycles of perception and action with their sketches, figures and paper constituted their thinking processes to make a model of the foldable food container.

5.2.7 Interactions with teachers

The participants’ interactions with their teachers was not strongly evident in the data as only two groups interacted with their teachers in an attempt to gain information about material properties and for the clarification of terminology. This is most likely due to the nature of this study, where I attempted to exclude the teachers’ influence on the participants’ cognitive processes. As such, the teachers merely acted as sources of information in my study. The way in which Groups A and C interacted with their respective teachers is captured in Excerpts 5.14 and 5.15.

P2: (move 55) The insulation material, which one is biodegradable?

P3: (move 56) Yes, that is the problem

P2: (move 57) Aluminum foil?

P3: (move 58) I don’t think foil is

P2: (move 59) Shall we get something halfway?

P1: (move 60) Well, it doesn’t say here (looks to teacher for a response)

T: (move 61) Aluminium foil is recyclable

P2: (move 62) Alright, so foil can work for us!

Excerpt 5.14: Group A’s interaction with a teacher

P3: (move 195) I read something here about it (plastic) is hard to clean.

P2: (move 196) Yeah, but that's the polystyrene.

P3: (move 197) (reads from the problem statement) Food vendors usually sell food to customers in plastic polystyrene containers. However, these containers do not retain the heat of the food inside the container for the trip home. Also, these containers are not easily recyclable because it is contaminated with food and difficult to clean. Because it is porous.

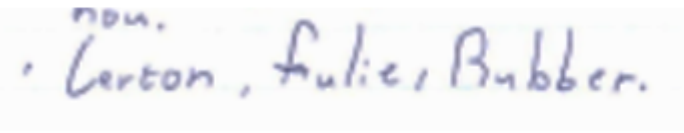
P3: (move 198) Sir, what does porous mean?

T: (move 199) It means that, it basically sucks in the food. So if you look at polystyrene there's small little holes where the food goes into those holes. Ok?

P3: (move 200) Yes, then it is not a big problem, we can just make it.

Excerpt 5.15: Group C's interaction with a teacher

These excerpts demonstrate the occurrences in which Groups A and C interacted with their teachers to gain information. In both of the excerpts the participants wanted to obtain information on the properties of materials for them to be able to make design choices. In Group A, prior to design move 60 where the participants asked information from the teacher, the participants brainstormed possible materials that could be used to make their food container, which fulfilled the requirement of biodegradability. The participants indicated an interest in aluminium foil, but seemed unsure whether or not this is recyclable and biodegradable. As a result, during design move 60, P1 inquired about this from the teacher, who responded that aluminium foil is recyclable, however omitting to mention that it is not biodegradable. Based on this response, P2 changed the requirement of biodegradability for the food container to recyclability, using aluminium foil as potential material in their specification list, as shown in Photograph 5.17.



nou.
· Carton, fulie, Rubber.

"Cardboard, foil, rubber"

Photograph 5.17: Final choice of cardboard, foil and rubber to make a food container

In Excerpt 5.17, Group C similarly asked their teacher for assistance to explain a term used in the problem statement that they did not understand. Prior to design move 198 where P3 asked for assistance, Group C was discussing the use of hemp plastic to make their food container. P3 however remembered that he had read from the problem statement that plastic containers are hard to clean from the design brief. In response, P2 indicated that this only referred to polystyrene, which prompted P3 to again review the problem statement in design move 197. Upon re-reading the problem statement, P3's attention shifted to the term 'porous', which he seemingly did not understand. This elicited his request in design move 198 to the teacher to explain the term porous. Once the teacher explained what porous meant in design move 199, P3 agreed with the rest of the group to use hemp plastic as a manufacturing material for their food container.

In terms of the types of design moves generated by each group of participants, Table 5.18 captures the directionality of the participants' thoughts when interacting with their teachers.

Table 5.18: Directionality of thoughts when interacting with teachers

Teacher interactions			
	Group A	**Group B**	**Group C**
Unidirectional forward	0	0	0
Unidirectional backward	0	0	0
Bidirectional design moves	2 (0.5%)	0	2 (1.2%)
Orphan moves	0	0	0

Table 5.18 indicates that the participants rarely interacted with their teachers during their design processes. Group B had no interaction with their teacher, while Groups A and C each had one such interaction. Both of these interactions produced bidirectional moves for in Groups A and C, which implies that the participants requested assistance from their teachers when trying to understand a previously generated thought. The nature of these moves can be further understood when reviewing the data in Table 5.19 below.

Table 5.19: Interactions with teachers when trying to achieve design problem solving goals

Design problem solving goals	Group A – teacher interactions	Group B - teacher interactions	Group C - teacher interactions
Understanding the problem	0	0	0
Understanding context	0	0	0
Understanding materials	2	0	2
Understanding weight	0	0	0
Understanding size	0	0	0
Understanding appearance	0	0	0
Understanding shape	0	0	0
Finding a suitable solution	0	0	0
Finding suitable materials	0	0	0
Finding a suitable size	0	0	0
Finding a suitable shape	0	0	0
Committing to a solution	0	0	0
Realising solution	0	0	0
Developing committed solution	0	0	0

As such, Table 5.19 indicates that both Groups A and C aimed to understand the nature of the materials that could be used to design their food containers when approaching their teachers for assistance. As revealed in the previously discussed excerpts (refer to Excerpt 5.14 and 5.15), Group A primarily wanted to understand whether or not aluminium foil is biodegradable, while Group C aimed to understand what the term ‘porous’ means.

Although the teachers were requested not to facilitate any thinking processes during the TAPS, the participants nevertheless interacted with the teachers to access information. According to Menary (2010), extended cognition should not be confused with ‘cognitive outsourcing’, which occurs when someone else completes a specific cognitive task for an individual involved in a cognitive task. I do not regard the fact that both Groups A and C relied on teachers as external resource, as cognitive outsourcing. I rather view this as a process during which the learners relied on their teachers to provide scaffolding for them to still complete their own cognitive task, after obtaining the necessary information. My view aligns with that of Bruner (1977), who advocates the notion of scaffolding. This view is furthermore consistent with proponents of extended cognition (Clark, 2008) who believe that extended cognition represents a joint product of intracranial processing, bodily input, and environmental ‘scaffolding’ (Walter, 2014). As such, this finding is consistent with previous studies in technology education (Xun & Land, 2004; Yeo & Quek, 2014) in terms of the design processes often followed by novice designers, who will access needed information from the social and physical environment in order to complete cognitive tasks.

5.3 INTERACTIONS BETWEEN PHYSICAL AND CONCEPTUAL STRUCTURES

In the last section of Chapter 4 and the first section of the current chapter, I have reported on the ways in which the various groups interacted with conceptual and physical structures respectively, and how these interactions contributed to the development of their design processes. In this section, I discuss how each group of participants interactively used both conceptual and physical structures during completion of their design tasks. As an introduction to my discussion, Tables 5.20, 5.21 and 5.22 provide overviews of the three groups’ interactive use of conceptual and physical structures.

Table 5.20: Group A's interactive use of conceptual and physical structures

	Scientific knowledge	Technological knowledge	Mathematical knowledge	Previous experiences	Previous instances	Total
Problem statement	0	6	0	0	0	**6**
Figure	1	11	22	2	14	**50**
Drawing	0	2	8	0	4	**14**
Written note	0	4	19	0	2	**25**
Physical object	0	0	6	0	1	**7**
Tool	0	0	37	4	0	**41**
3D model	0	9	6	0	1	**16**
Teacher	0	1	0	0	0	**1**
Total	**1**	**33**	**98**	**6**	**22**	**160**

Table 5.20 indicates that Group A generated 160 conceptual-physical interactive design moves out of a total of 393 design moves (40.7%) they created. When interacting with figures, Group A was able to make connections with both their technological knowledge (11 instances), and mathematical knowledge (22 instances), and also to recall prior instances of design choices during their design process (14 instances). Their use of mathematical knowledge required of them to interact with written notes (19 instances) and tools (37 instances).

For Group A's design process, it therefore seems evident that figures, tools and written notes facilitated engagement by the participants with their technological and mathematical knowledge as well as prior instances. However, Group B's interactive use of conceptual and physical structures was different, as shown in Table 5.21 below.

Table 5.21: Group B's interactive use of conceptual and physical structures

	Technological knowledge	Mathematical knowledge	Previous experiences	Total
Problem statement	4	1	7	**12**
Figure	8	1	0	**9**
Drawing	0	0	5	**5**
Written note	3	0	0	**3**
Physical object	12	8	4	**24**
Tool	0	2	0	**2**
Textbook	3	0	0	**3**
Total	**30**	**12**	**16**	**58**

Table 5.21 shows that Group B generated 58 conceptual-physical interactive design moves out of a total of 160 design moves (36.3%), which represents a ratio similar to that of Group A. Table 5.21 furthermore indicates that Group B's interaction with technological and mathematical knowledge, as well as prior experiences specifically occurred when they were interacting with physical objects and the problem statement. Although Group B scarcely interacted with the problem statement during designing, their interactions with physical objects nonetheless directed their attention to technological knowledge and previous experiences.

Group C's interactive use of conceptual and physical structures, as shown in Table 5.22, differed from Group A and B's processes. Overall, Group C's simultaneous interaction with these structures generated less design moves than in the cases of Groups A and B.

Table 5.22: Group C's interactive use of conceptual and physical structures

	Scientific knowledge	Technological knowledge	Mathematical knowledge	Previous experiences	Previous instances	Total
Problem statement	0	3	0	0	0	**3**
Figure	6	5	0	12	1	**24**
Drawing	0	2	0	17	1	**20**
Physical object	1	1	1	3	0	**6**
Tool	0	0	2	0	0	**2**
Teacher	0	2	0	0	0	**2**
Total	**7**	**13**	**3**	**32**	**2**	**57**

As indicated by Table 5.22, Group C only generated 57 conceptual-physical design moves out of 231 design moves (25%), which is a bit less than both Groups A and B. Group C's recall of prior experiences was mostly facilitated through their interactions with figures and drawings, while their use of technological knowledge was seemingly enabled by their interactions with the problem statement and figures. Group C's limited interaction between conceptual and physical structures implies that they did not easily make connections between their internal and external worlds during designing. When provided with a physical information source, Group C would thus only pay attention to information that was directly perceivable without connecting it to conceptual sources, and *vice versa*.

In summarising the participants' use of various conceptual and physical sources, Figures 5.13 to 5.15 illustrate the way in which the participants interacted with information sources in the extended design task environment. At first glance, Figures 5.13 to 5.15 capture how different information sources were used by each group. The archiographs furthermore illustrate how thoughts might have originated through interaction with one type of source, on the left side, and then on the right side of the arch, how this thought is referred to, elaborated or evaluated during a subsequent design move. For example, the participants might have started to generate a design idea when looking at a figure (magenta), but then modified the proposed idea in a later design move during a sketching activity (cyan).

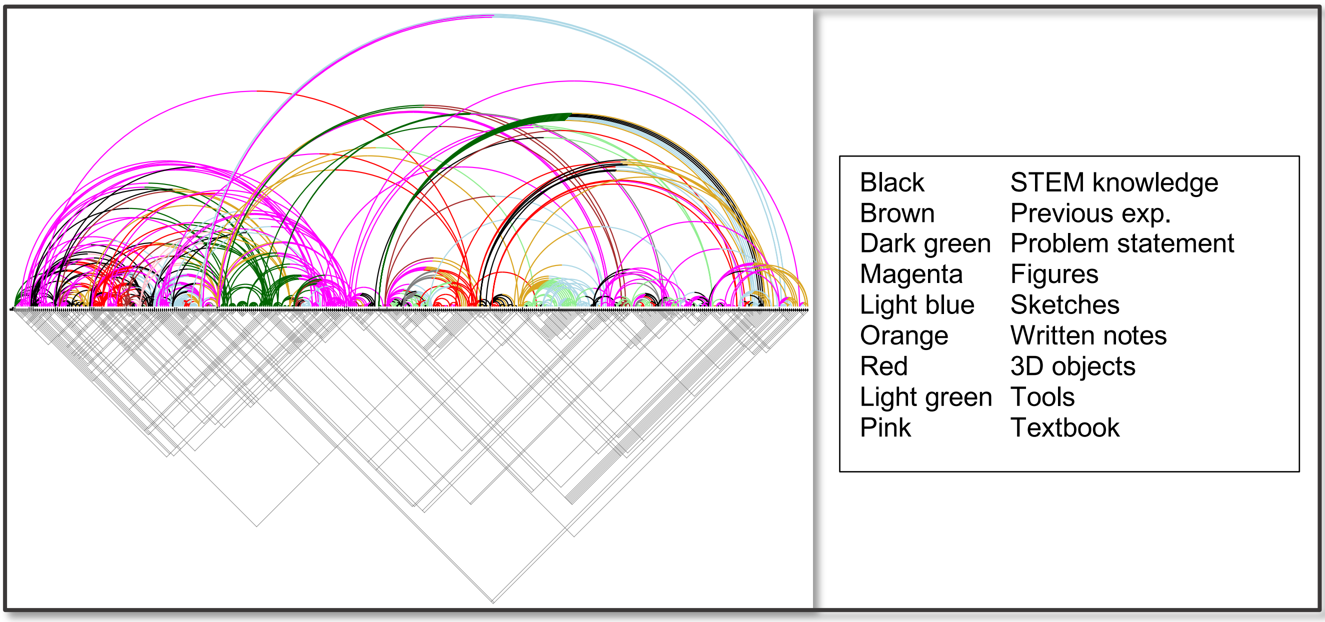


Figure 5.13: Linkograph and archiograph of Group A’s interactions with conceptual and physical structures

Figure 5.13, captures the links that Group A made between design moves, while interacting with conceptual and physical structures. In this regard, Group A generated a large number of links in the beginning of their design process, while they were engaged with various information sources. This seemingly occurred as a result of their immediate engagement in problem solving cognitive phases. During the first part of the design move distribution, it can be seen that their interactions with figures (magenta), STEM knowledge (black) and 3D objects (red) played a role in their connection making between thoughts. Furthermore, it seems as if Group A’s interactions with figures (magenta), sketches (light blue) and written notes (orange) generated some of the longest link spans, i.e. the distance between two design moves, which implies that it supported the participants’ working memory limitations.

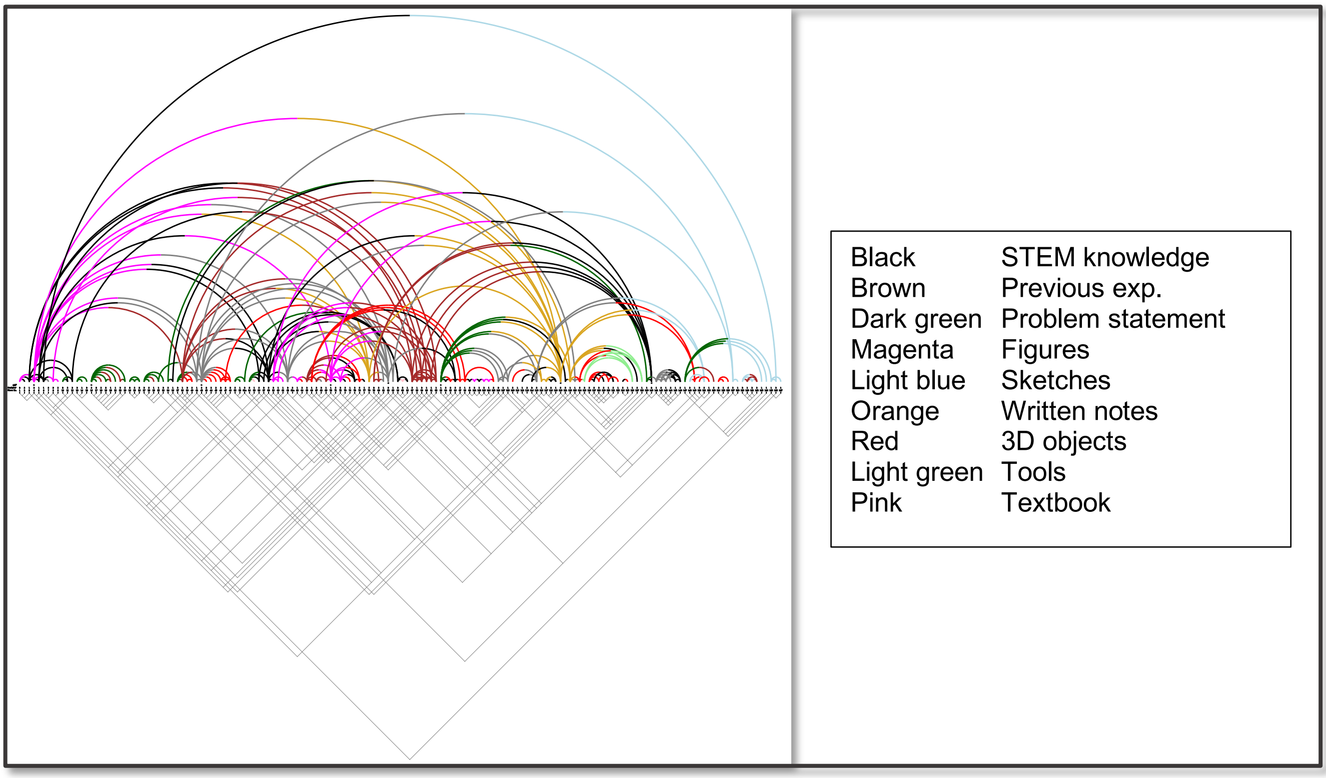


Figure 5.14: Linkograph and information use of Group B

In contrast to Group A, Group B made less links between design moves, and the majority of their linking activity occurred during the middle of the design move distribution. Similar to Group A, Group B also generated large link spans, which were facilitated by their interaction with STEM knowledge (black), sketches (light blue) and written notes (orange).

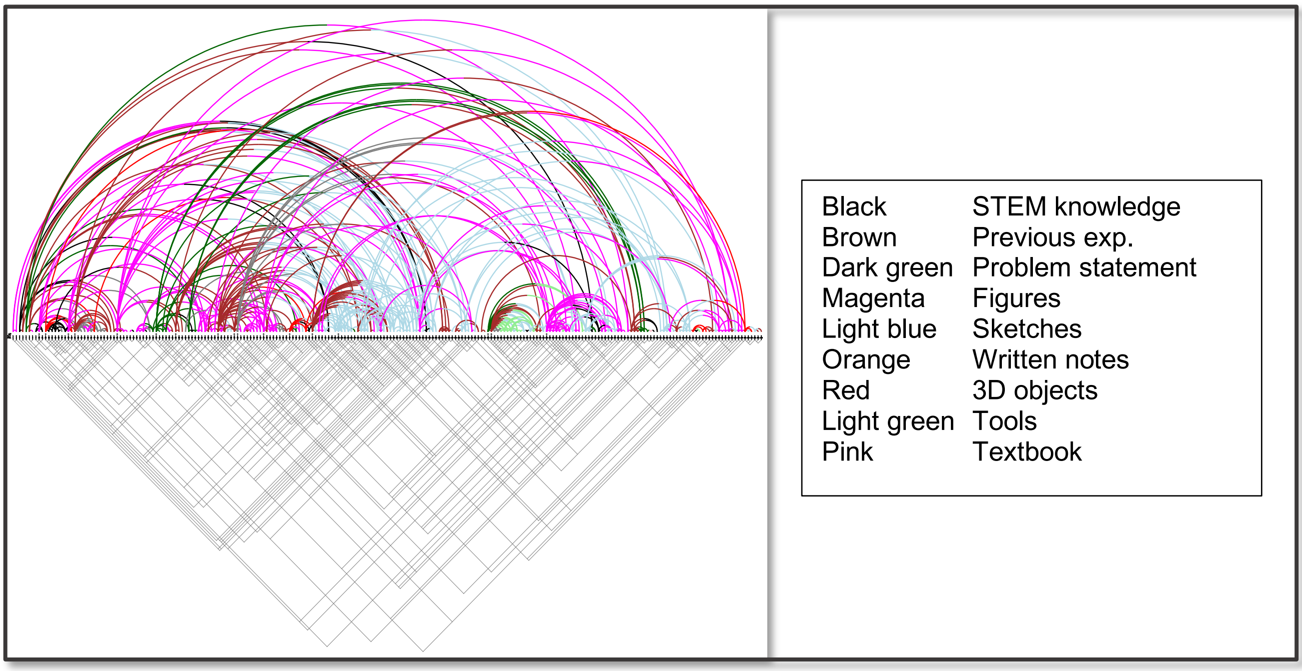


Figure 5.15: Linkograph and information use of Group C

Figure 5.15 shows that Group C's linking activity differed from those of Groups A and B, as their thoughts displayed progressive had an increased interconnectivity. In this regard, Figure 5.15 indicates that the majority of their linking activities were facilitated by interactions with figures (magenta) and their previous experiences (brown) and sketches (light blue). Similar to Groups A and B, Group C also generated large link spans as a result of their interactions with figures (magenta), previous experiences (brown) and the problem statement (green).

The results on the various groups' interactive use of conceptual and physical structures relates to the theoretical assumptions of Extended Design Cognition Theory, which states that external information sources will function as scaffolds and constituents of internal cognitive processes (Haupt, 2015). Internal cognitive processes will in turn extend into the environment from which they can be manipulated (Menary, 2017). This is particularly demonstrated in the way that external sources supported the working memory limitations of the learners participating in my study, as seen in the large link spans. In support of this result, Goldschmidt (2014) notes that since design moves represent brief instances of thought, it cannot be expected that they will generate many backlinks to previous design moves, as those moves may have already faded away from the working memory.

However, Figures 5.13 to 5.15 show that, while interacting with physical structures, it is possible for learners to overcome their working memory limitations. This finding is supported by Extended Cognition Theories (Carter et al., 2018; Heersmink, 2016; Walter, 2014). In support, Rowlands (1999), for example notes that that there is no valid reason for viewing working memory as purely internal, but rather describes it as ‘hybrid’ in character, consisting of both internal and external processes. As such, the results obtained by the linkographs supports the view that the physical environment forms part of learners’ cognitive processes, especially to support limitations in working memory.

From an Activity Systems view, the participants’ simultaneous interactions with physical and conceptual structures relate to the internalisation and externalisation principle of Activity Systems Theory (Engeström, 2015; Kaptelinin & Nardi, 2006). This principle holds that object-oriented activities contain both internal and external structures (Engeström, 2015; Kaptelinin & Nardi, 2006). On the one hand, internalisation refers to the process during which conceptual ideas and thoughts are formed, based on learners’ interactions in the environment. Based on the results indicated in Tables 5.20 to 5.22 and Figures 5.13 to 5.15, internalisation points to instances where the learners interacted with physical structures (such as figures), that in turn triggered interaction with conceptual structures (such as technological knowledge). On the other hand, externalisation related to the way these conceptual ideas manifested in the physical environment.

Currently, limited research methodological strategies exist for studying the interplay between conceptual and physical structures, and how this may contribute to the development of design ideas (Tedjosaputro & Shih, 2018). A recent literature survey conducted by Grubbs et al., (2018) confirms that the majority of the coding schemes used to characterise learners’ design cognition is based on traditional cognitive science theories according to which thinking is seen as residing in the mind without acknowledging the role that external aids and scaffolds may play during designing. As such, by using an Extended Design Cognition Theory framework, this study adds new insight concerning the extended cognitive processes of learners during designing. The ongoing need for continued research on learners’ design cognition however remains, in striving to transcend the internalist boundaries of cognitive science. Such research may add to a more holistic and situated view on design cognition.

5.4 CONCLUSION

In this chapter, I discussed the participants' interactions with science, technological and mathematical knowledge, as well as their access to previous experiences. I more specifically focused on the types of thoughts that were generated as well as how the conceptual structures assisted the participants to achieve their problem solving goals. Furthermore, I relied on both qualitative and quantitative data on the participants' interactions with the problem statement, figures, drawing and written notes, as well as textbooks during their problem structuring and problem solving cognitive phases in presenting my results. I concluded the chapter by foregrounding the manner in which the participants integratively used conceptual and physical structures.

In the following final chapter of the thesis, I provide an overview of the study, before addressing the research questions and coming to final conclusions. I furthermore contemplate the contribution of the current study and reflect on some limitations and challenges I encountered in conducting the study. I conclude the thesis with recommendations for training, practice, policy and future research.

CHAPTER 6

FINAL CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

In the previous two chapters, I presented the results I obtained and discussed the findings of this study against the background of the literature I included in Chapter 2, related to learners' use of social, conceptual and physical structures during designing. Throughout, I relied on quantitative and qualitative data to substantiate and enrich my discussions.

In this chapter, I first provide an overview of what has been presented in this thesis. Next, I come to conclusions in addressing my research questions, as formulated in Chapter 1. I then reflect on the challenges I experienced during the course of this study. I present the theoretical, methodological and practice-based contributions and conclude with recommendations for teacher training and practice, policy, and future research in the field of learners' design cognition in STEM education.

6.2 OVERVIEW OF THE PRECEDING CHAPTERS

Chapter 1 provided background information on my study. I introduced and justified my focus on learners' design cognition in the context of STEM education, stated the purpose of the study, and formulated research questions. I contextualised the key concepts and foregrounded the working assumptions with which I undertook this study. I furthermore introduced my conceptual framework, explaining how I integrated Extended Design Cognition and Activity Systems Theory to investigate how learners interact with social, conceptual and physical structures during designing. I briefly described the paradigmatic and methodological choices I made, as well as the ethical principles I respected. Finally, I referred to the quality criteria I considered in order to ensure a trustworthy and rigorous study. I concluded Chapter 1 by providing an overview of the structure of the thesis.

In **Chapter 2**, I reviewed existing literature relating to the nature of technological knowledge, objects, activities and volition, in order to provide a basis for understanding the way in which learners may design socio-technological objects. This was followed by a historical overview of viewing designing as problem solving where General Systems Theory is used as a meta-theoretical framework in which Extended Design Cognition and Activity Systems Theory could be situated. I concluded Chapter 2 by explaining the conceptual framework I compiled, that guided my investigation of learners' interactions with their internal conceptual structures, as well as the physical and social structures in the design task environment.

In **Chapter 3** I explained the empirical investigation I conducted. I discussed and justified my decisions to take a critical realist stance, follow a mixed-methods approach and utilise a multiple case study design within the technology education context. I explained the way in which I combined convenience and purposive sampling to select three cases, involving nine learners as participants who were top performing learners in Science, Mathematics and Technology. Next, I described how I planned and executed data generation, documentation and analysis around a TAPS methodology in which I created a STEM task. For data analysis, I specifically focused on explaining how I implemented linkography as underpinning analysis method based on the generated utterances and concurrent external representations that the participants created during their design processes. I conclude the chapter by comprehensively discussing the quality assurance measures and the ethical guidelines I adhered to in completing a rigorous and ethical study.

Chapters 4 and **5** focused on results and findings. In these chapters, I presented the results and discussed the findings in terms of five main aspects, being the general linkography analyses of each group of participants' design processes; the social interactions of each group of participants during designing; the participants' interactions with conceptual structures; the participants' interactions with physical structures; and finally, the participants' simultaneous interactions with conceptual and physical structures. My discussions in Chapters 4 and 5 serve as background to the conclusions I come to in this chapter, against the framework of existing theory (Chapter 2) and the conceptual framework that guided my investigation.

6.3 ADDRESSING SECONDARY RESEARCH QUESTIONS

In this section, I address the secondary research questions formulated in Chapter 1, based on the findings I obtained. The next section focuses on my conclusions in terms of the primary research questions and the theoretical, methodological and practice-based contributions of this study.

6.3.1 **Secondary research question 1:** How did the social interactions of the learners shape the emergence of their design processes?

In the context of this question, the word ‘social’ is used to imply how individual participants contributed to the collective design process and how they generated links between their own and each other’s design moves. The groups that participated in this study comprised three members each, and were instructed to work collaboratively. However, all of the groups had one member that contributed significantly less design moves than the other two members of the group. This could be seen in the number of design moves they produced, the number of links generated, as well as the formulation of critical moves.

Across the three groups, individuals were seen to contribute different types of design moves that engendered their design processes. The value added to the process by social interaction lies in the fact that some participants mostly generated critical forward moves, while some participants mostly generated critical backward design moves. Analysing the participants’ processes in terms of intrapersonal and interpersonal links further show that the participants in each group were dependent on each other’s design moves, suggesting that their design moves constituted each other's cognitive processes.

From an Extended Design Cognition point of view, design moves constitute both sequential and consequential building blocks in the construction of the design process. In this regard, I argue that the social interactions of individual learners within the group context can act as both prompts and parameters for the generation of subsequent design moves. This implies that when technology learners complete a design task in groups, they will probably tend to produce links between their own and each other’s design moves in order to reach their problem solving goal.

6.3.2 **Secondary research question 2:** How did the learners' interactions with conceptual structures contribute to the emergence of their design processes?

For the purpose of this study, 'conceptual structures' refers to STEM knowledge, prior experiences and prior instances of the design process. In view of the diverse interactional patterns related to conceptual structures, I argue that this type of interaction is uniquely contextual and dependent on the type of the design task and the constitution of the group. This is exemplified by my findings indicating limited use by the participants of scientific knowledge; technological knowledge being used liberally by everyone; mathematical knowledge being used extensively by one group only; and prior experiences being relied on extensively only by two groups. This level of diversity characterises the participants' interactions with conceptual structures during the problem structuring and problem solving phases respectively.

Although the participants interacted in different ways with conceptual structures, these interactions probably contributed to their achieving various emergent problem solving goals. The goals served as milestones in their journey towards solving the design problem, thereby implying that, without these interactions, some of their decisions would have been uninformed. I can therefore conclude that this particular type of interaction is foundational to constructive engagement during designing.

The participants' interactions with conceptual structures generated a substantial number of different types of design moves. Based on this finding, I posit that the diversity of their interactions with conceptual structures did not inhibit the generation of useful and productive design moves. More specifically, technological knowledge was the only conceptual structure with which the participants interacted, which resulted in a substantial number of bidirectional design moves. Therefore, I argue that technological knowledge can be seen as an important mechanism that may facilitate the shifts between generative and evaluative thinking. If applying this principle in integrated STEM education, learners can thus engage in bidirectional thinking, linking past and future thoughts, by engaging with technological concepts.

6.3.3 **Secondary research question 3:** How did the learners' interactions with physical structures facilitate the emergence of their design processes?

Within the context of this study, 'physical structures' refer to external information sources, which include the problem statement, figures provided to the participants, sketches, written notes, tools, physical objects, 3D models, textbooks and teachers. The findings of my study indicate that the use of physical structures contributed to the participants achieving many of their problem solving goals. Their interactions with physical structures engendered design moves that led to both the widening and narrowing of the design problem space. This was confirmed by their generation of unidirectional and bidirectional design moves.

Physical structures, including figures and physical objects, provided the participants with the necessary information enabling them to allow them to perceive and act in order to structure and solve their design problems. These affordances were captured in visual elements such as shapes, textures, lines, sizes and colours, which provided scaffolds for their instantiation of design moves.

The findings furthermore highlight the trend of the learners to strongly engage with the problem statement, figures and written notes during the problem structuring phase, while depending more strongly on figures, drawings and physical objects during the problem solving phases. In all of the cases, these physical structures generated more design moves than the conceptual structures. As such, the participants relied more heavily on external information than on their disciplinary knowledge and prior experiences to understand and solve their design problems.

Although the participants' interactions with physical structures generated a substantial number of productive design moves, it also led to the participants developing solutions similar to those provided in the visual examples, albeit with some adjustments. In their attempt to find suitable solutions, the participants reasoned around specific visual examples. These reasoning processes entailed the application of various cognitive operators, including proposing, elaborating, justifying and modifying, yet as they were guided by for example physical structures, the final ideas were not highly innovative by nature.

Based on the findings I obtained, I can thus conclude that physical structures may have both a positive and negative effect on designing by novice designers, depending on the nature of the design task. While the use of physical structures allowed the participants in my study to gain insight into the design task, and inspired some of their design moves, this at the same time hampered their originality as they began to mirror the visual examples of solutions instead of innovatively designing something new. However, the instructions in the problem statement did not specify that the design had to be innovative, thus it did not impact the results or findings of this study. This is thus merely noted as an interesting finding that emerged from an observation.

6.3.4 **Secondary research question 4:** How did the learners interactively use conceptual and physical structures during their design processes?

In this study, conceptual-physical interactions refer to instances during the design process when the participants accessed and used internal and external information sources. It was clear that the figures, written notes, physical objects and tools in the environment triggered the use of mainly mathematical and technological knowledge. Furthermore, archiographs, in combination with linkographs captured how the participants interacted with physical structures in the design task environment in order to support their working memory limitations. Therefore, I posit that cognitive processing during designing consists of both internal and external processes that are necessary for completing cognitive tasks.

This finding confirms some recommendations made in Ecological Psychology, which suggest that teachers need to engage in the education of intention and attention. This recommendation is based on the view that not all information is stored in the memory, but that the physical environment rather provides sufficient information in terms of scaffolds and affordances, for perception and action to directly proceed without the need for information recall or any other internal cognitive processing. Educating for intention and attention refers to teachers who, on the one hand induce learners to adopt new problem solving goals during their design processes, while on the other hand, attuning learners' attention to environmental stimuli which they might not have noticed on their own.

Based on the findings of the current study, I argue that conceptual-physical interactions do not necessarily imply a many-to-many association, but may in fact merely serve as trigger of certain elements within one domain by particular elements in the other. This argument would explain that and why, in this study, the learners' thought processes as connected to their use of a specific tool were not random. For instance, the use of a scale or ruler by the learner participants was intentionally connected to their use of mathematical knowledge when they wanted to achieve the problem solving goal of finding a suitable size for their design. As such, in this case, the intention to find a suitable size informed their use of specific tools in achieving a specific goal.

6.3.5 **Sub question 5:** To what extent can linkography be utilised to understand technology learners' thought generation during designing?

I selected linkography as this choice implied the possibility of focusing on the design cognition actions of the three groups of participants' thoughts on a microscopic level. Through the use of linkography, I was able to summarise each groups' design process in terms of the number of design moves that were generated, the number of links produced between design moves, and the resultant link indexes. In this way, I could determine the productivity and connectivity of each group's design process.

The STEM task given to the learners in the current study required them to design a heat retaining container that was also biodegradable and recyclable. Participants were provided with various tools and materials to assist in their designing. This allowed me to observe the systematic moment-to-moment decisions that were made as participants interacted with the various tools and materials, and with each other. This further allowed me to observe how they were able to draw on previous knowledge and experiences, as well as prior instances in the design process. Linkography did not only enable me to see which social, conceptual and physical structures generated new thoughts, it furthermore provided me with a macroscopic view of how these thoughts were interconnected by means of visual representations.

A conventional linkograph simply indicates how the design process can be segmented into design moves and how these design moves are connected to each other. In this study, I adapted linkography as I linked the social, conceptual and physical structures to these design moves. Furthermore, I included bicoloured archiographs, to improve the illustration of connectivity between links, and to demonstrate potential causality between two design moves.

Through linkography, I could characterise the different design moves that were generated in terms of unidirectional forward, unidirectional backward, bidirectional, orphan and critical design moves. Each of these design moves served as descriptors of the thought generation processes, involved during the learners’ design problem solving processes. Unidirectional forward design moves implied that the participants were generating new thoughts or ideas without considering any previous thoughts. Unidirectional backward design moves implied that the participants generated thoughts that reflected or evaluated previously instantiated thoughts without any reference to future design moves.

Bidirectional design moves involved thoughts that had links to previously generated as well as future generated design moves. The fact that the majority of the learners’ design processes were characterised by bidirectional moves suggests that the participants were rapidly shifting between divergent and convergent modes of thought. Although this observation was conducted on a fine-grained level of analysis, this finding is consistent with existing literature in the field of creative cognition, which suggests that creativity is the result of designers’ ability to shift between divergent and convergent modes of thought.

Critical design moves are rich in links and were significant as they were indicators of design moves that either generated or evaluated a significant number of other design moves at one instance. Critical design moves were the indicators of instances where the participants made design choices.

In this regard, the results showed that groups generated a limited number of orphan moves, which shows that their design processes were interconnected and not isolated. This may imply that they were able to see the implications of their design choice for past and future design moves. In terms of the unidirectional design moves, the participants generated more unidirectional backward design moves compared to unidirectional forward moves. However, when looking at their critical moves, they generated more critical forward design moves than critical backward design moves.

This implies that although the participants experienced continuous evaluative thoughts, it was not significant enough to be classified as critical moves. The other implication is that when one considers the ratio between critical forward and backward moves, the participants were unable to generate thoughts that were critical in developing, exploring, or summarising previously generated thoughts.

In summary, using linkography in this study enabled me to understand the learners' thought generation by providing both quantitative and qualitative data that revealed the learners' thought connectivity and thought directionality. In the field of design and technology, this is particularly useful for researchers who strive to understand how learners' design ideas come into being.

6.4 FINAL CONCLUSIONS AND CONTRIBUTIONS OF THE STUDY

In this section I present the contributions of this study, by reflecting on the two formulated primary research questions. As such, I address the following two questions:

- How can insight into learners' interactions with social, conceptual and physical structures during designing inform existing theory in design cognition? *(Theoretical contribution)*
- How can the implementation of linkography inform the development of methodologies suitable to investigate learners' design cognition? *(Methodological contribution)*

I also present the practical application value of my study based on the findings I obtained.

6.4.1 Theoretical contribution

The findings of this study add to the emerging body of knowledge on novice designers' cognitive processing during designing. More specifically, this study makes an ontological contribution in terms of the basic structures, mechanisms and events underpinning learners' design processes. Theoretically, this study contributes to existing literature by providing a novel framework (refer to Chapter 2) for understanding how novice designers' interactions with social, conceptual and physical structures contribute to the emergence of their design processes, building on initial theories on Extended Design Cognition, yet adding the dimension of socially extended design cognition.

By studying novice designers' way of designing from an Extended Design Cognition and Activity Systems point of view, I was able to gain insight into the manner in which learners may use social, conceptual and physical structures to incrementally develop their understanding of a design problem; identify, plan and develop suitable solutions; and evaluate some of the choices they made. Even though I based my conceptual framework on theory related to expert design practice, certain links emerged between the nature of novice and expert design cognition, for instance, the fact that both novice and expert designers engage in different cognitive phases during designing; and the similarities between the manner in which novice and expert designers generate unidirectional, bidirectional and critical moves. These findings and indicated application of theory on expert designers within the context of learner designers, confirm the theoretical contribution of my study. In addition, theory may ultimately inform practice in terms of the ways in which novice design education can be offered and potentially improved in schools.

The design process can be viewed as a complex process that should be considered in terms of four foundational aspects, namely social, conceptual, physical and conceptual-physical interactions. These interactions can provide scaffolding for each other, leading to the emergence of the design process. As my study provides incontrovertible evidence that design cognition does not depend on the creation of something from nothing; but rather emerges from interactions that involve backward and forward design moves, with social, conceptual and physical interactions, the existing knowledge base on learners' design cognition is extended by means of the findings I obtained.

More specifically, the novel conceptual framework that I compiled for this study allowed me to observe how learners' cognitive processes are constituted by social, conceptual and physical structures. This is significant as prior studies in design cognition tend to emphasise the development of mental states without acknowledging the role of the social and physical environment. Therefore, the findings of the current study add to Haupt's (2015) Extended Design Cognition Theory by integrating the use of Activity Systems Theory (Engeström, 2015) when studying and attempting to understand design cognition. This integration allow researchers to focus on the way in which the physical and social environment may constitute designers' cognitive processes.

In terms of the findings of this study, my study more specifically illustrates how learners are able to generate thought structures that are often similar than the thought structures of expert designers, in terms of bidirectional design moves. However, in contrast to expert designers, learners will not generate sufficient critical backward design moves. As such, it can be concluded that novice designers in school environments may not necessarily engage in sufficient evaluative thinking during designing, which once again hold practical application value for STEM teachers in practice, in order to support learners in developing design skills.

By using linkography, my study furthermore contributes to existing theory on collaborative designing, by illustrating how learners incrementally build on each other's and their own ideas to achieve synthesis in their understanding of a design problem, and their design solutions. In terms of learners' interactions with conceptual structures, my findings contribute to the emerging literature base on integrated STEM education, more specifically in terms of current conceptualisations of the ways in which learners do and do not integrate knowledge stemming from the STEM domains, to solve design problems.

In terms of learners' interactions with physical structures, my study revealed two underlying mechanisms of learners' interactions with physical structures, namely perception-action and intention-attention dynamics. These two mechanisms may enable learners to detect functional information in the external environment, which they can then use to realise their design intentions during problem structuring and problem solving phases. This knowledge adds to the existing theory on learning in design environments, more specifically in terms of the way that learners search for information to realise their design intentions.

6.4.2 Methodological contribution

The current study contributes to the repertoire of possible methods that may be employed when studying technology learners' design cognition. In this study I have namely demonstrated how linkography can be used as a TAPS analysis method to better understand the nature of learners' design cognition during a STEM task. This is a relatively new avenue of study in the field of technology as it has gained limited attention in school-based design contexts. More specifically, linkography as methodological strategy has primarily been applied in the fields of architecture (Goldschmidt, 2014) and performing arts (drama improvisation) (Hatcher et al., 2018). By utilising this method, in a rather unfamiliar context, I attempted to add to the repertoire of techniques that can be used when investigating an abstract field of study with novices as participants. As such, my study may contribute to suitable research methodology in the field of technology education, by introducing this emerging method as avenue to explore learners' design cognition. Even though ongoing research is required in this field, my study provides a stepping stone in this direction.

In my study, I specifically relied on linkography to visually represent the complex nature of the design processes, in order to emphasise the generative and evaluative nature of thinking during designing. I further adapted linkography, in its initially intended format by focusing on the various social, conceptual and physical structures involved in generating design moves. This method of research subsequently availed both qualitative and quantitative avenues to better understand how learners think during designing. Furthermore, I included archiographs in my presentation of the results, once again providing an example of an alternative application of linkography in a context not initially intended for this methodology.

Finally, my study also contributes to the existing repertoire on the application of TAPS methodology. As conventional protocol studies predominantly emphasise internal cognitive processing at the expense of understanding the role of the social and physical environment during designing, I adapted the way in which TAPS procedures are typically applied in design environments. I namely included a focus on learners' interactions within the physical and social environment, in order to be able to engage on deep levels of analysis, focusing on the factors that may contribute to learners' cognitive processes during designing. As such, my study provides an example of a potentially innovative approach to researching design cognition in STEM learning environments.

6.4.3 Contribution for STEM education practice

Based on the findings of this study, insight in terms of unguided novice design behaviour may potentially guide technology teachers and STEM practitioners in working with STEM subjects. Teachers and practitioners may benefit from being aware of how learners engage in design thinking during ill-structured design problem solving processes, applying what they gain from the findings of this study to their daily classroom activities.

Based on the findings of my study, and conclusions I came to, I propose a model that may be used for training current and future technology teachers and STEM practitioners, as depicted in Figure 6.1. The model I propose highlights the various components that teachers may rely on when planning and implementing STEM tasks, embedded in the early phases of the design process.

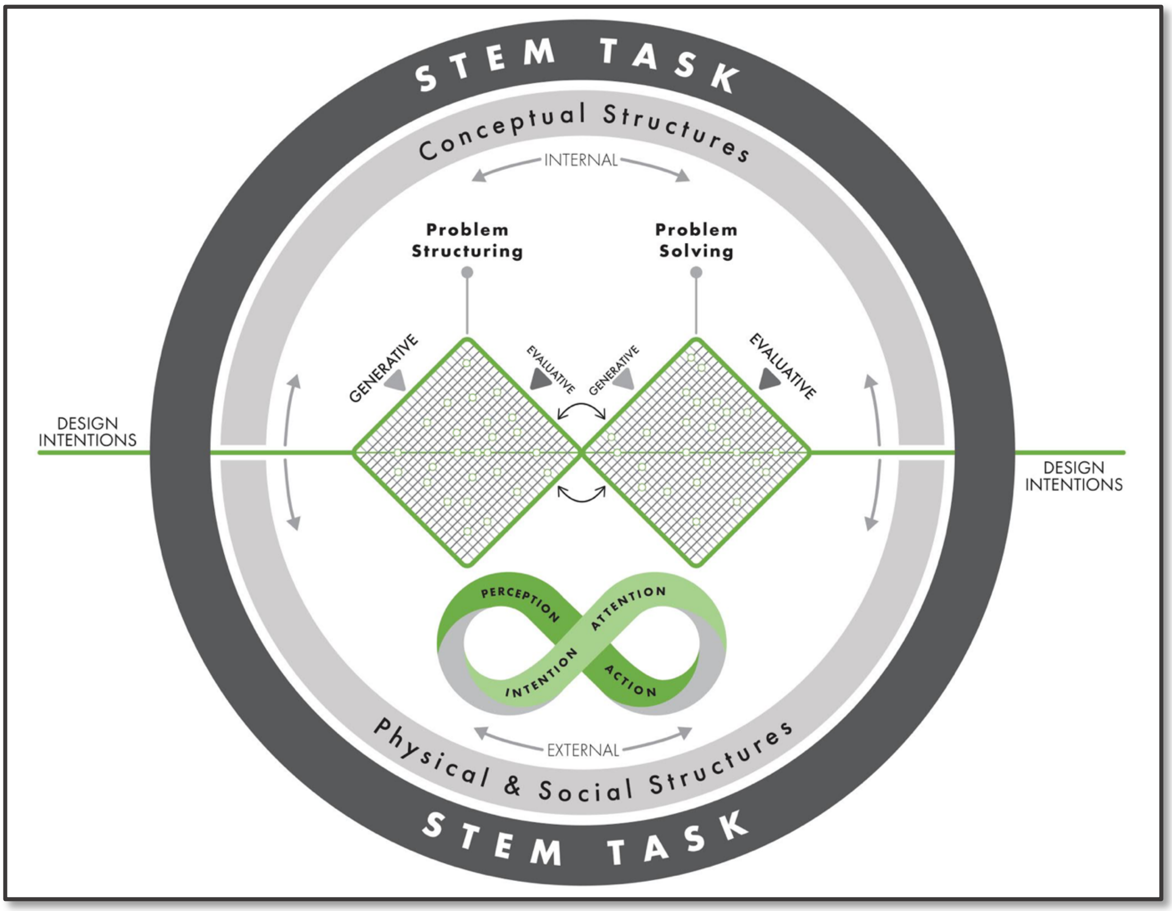


Figure 6.1: Training model for future STEM practitioners

This training model highlights the central role of the social, conceptual and physical environments in which STEM tasks are embedded. As indicated by my study, these environments will play a vital role in scaffolding learners' design processes as sources of information and potential mediators during the early phases of the design process. Learners will namely engage with these environments by means of internal cognitive processes such as remembering, and recalling; while interacting with external environments through perception-action cycles and intention-attention dynamics. As learners progress with their design processes they will probably engage in continuous cycles of thought generation and evaluation which will in turn lead to the synthesis of design ideas and an understanding of the design problem.

If being exposed to, and understanding the proposed model, STEM practitioners and technology teachers may gain insight into the nature of novice designers by heeding the structure of the extended design task environment, and the way in which it may influence learners' problem solving spaces. As such, they may be able to plan for influential factors, in order to support learning and creative problem solving amongst learners. As my findings provide evidence that learners require access to social, conceptual and physical information sources to allow for effective problem structuring and problem solving, learners need to be taught how to recall relevant STEM knowledge or prior experiences, perceive information afforded by external environments and act on it, as well as heed their design intentions.

6.5 RECOMMENDATIONS

In conclusion, I formulate some recommendations for teacher training and practice, potential policy implementation, and future research, in an attempt to facilitate improved novice design cognition practice in the STEM education context.

6.5.1 Recommendations for teacher training and practice

Based on the findings that I obtained, I recommend that pre-service and in-service teachers be trained in an extended design cognition approach. In this way, awareness of the socio-cognitive and physical environments in which learners' design processes are embedded can be raised. By doing this, STEM teachers may be empowered in terms of lesson planning according to an open systems perspective, while being cognisant of the various social, conceptual and physical structures that may support or perhaps impede learners' design problem solving in STEM environments. Incorporating various social, conceptual and physical structures in extended design task environments has the potential of enriching learners' thinking processes beyond routine thought processes, and to provide opportunities for bidirectional thinking to form the foundation of learners' design processes.

In fostering learners' thinking processes during designing, I recommend that teachers be introduced to the generative and evaluative nature of designing. For this purpose, teachers may be introduced to the model I proposed in the previous section, enabling them to facilitate effective novice design processes. In this way, teachers may recognise opportunities to scaffold learners' thought processes by means of questions, prompts and environmental attunement or explication of knowledge that can generate forward and backward links during designing. Teachers may as a result be able to foster productive design processes that is characterised by high levels of interconnected thoughts.

In terms of the results related to the application of linkography, I recommend that teachers and prospective teachers be trained to create thinking tools that may facilitate learners' awareness of their generative and evaluative thinking processes so that they may potentially know when to generate new thoughts and ideas, and when to evaluate what they have already thought of. Thinking tools, including those that can foster critical forward moves (divergent thinking) and critical backward moves (convergent thinking) can be developed to support learners' thought processes during designing. Furthermore, such tools may be used during instances where learners are overwhelmed by uncertainty or fixated on problem and solution aspects, in order to generate new avenues of thought.

I also recommend that STEM teachers introduce and develop learners' modes of externalisation in terms of verbal and visual communication methods, in further support of learners' interconnected thought processes. In this regard, learners' external representations, including verbal interactions, drawings, 3D modelling and writing can be utilised as tools for design reasoning, which may in turn facilitate learners' own and others' generative and evaluative thought processes.

Next, I recommend that teachers should be trained in developing and using ill-structured design problem solving statements. This implies that teachers can be trained to provide learners with sufficient opportunities where they are confronted with uncertainty, and to guide learners in their social, conceptual and physical environment in order to find out what they do not know about the problem and potential solutions. Such guidance may be facilitated by means of a knowledge-rich environment in which questioning, demonstration, and critical and creative thinking can be fostered.

Finally, the current teaching of designing in the technology classroom may be enhanced if teachers themselves are acquainted with the relevant informational sources, other than textbooks, to which learners may be attuned when missing information is required. It is similarly important for teachers to recognise when learners may need guidance, and to be able to induce students to adopt new problem solving goals so as to create new intentions. This may in turn facilitate an unfolding of learners' intention-attention dynamics as they perceive and act upon the external environment to reach stipulated and self-generated design problem solving goals.

6.5.2 Recommendations for Policy Implementation

Although the potential for learners' thinking is demonstrated in this study, the facilitation of STEM activities in the classroom depends on research-based policy development and implementation. While the findings of this small scale study may have limited impact on policy makers, I believe that the findings may highlight the need for long-term STEM policy development. As such, I recommend ongoing debate between researchers, STEM teachers and policy developers on how to bridge the gap between the theory on novice design cognition and the practical implementation thereof *via* curriculum development.

More specifically, the findings of this study highlight the need to recognise novice design cognition and learners' ability to efficiently access information within social, conceptual and physical environments. Based on current research on learners' STEM performance in South Africa, a need clearly exists for curriculum writers in STEM subjects to develop workable guidelines that can promote the development of learners' design capabilities. Adopting approaches, such as STEM education, implies the possibility that research-based policy making may inform transformation in terms of the way teachers implement STEM curricula. As limited guidelines are currently available for STEM education, and technology teachers in particular, to facilitate generative and evaluative thinking processes during learner's design processes, I recommend that the national curricula be revisited in order to include clear guidelines for effective facilitation tools and teaching techniques for teachers of technology.

Furthermore, findings of the current study indicate that the participating learners did not interact with their textbooks, which is prescribed by the Department of Basic Education in the CAPS document. As such, it seems as if textbooks, for the most part, may not necessarily assist learners to complete a design task. It follows that the use and content of current textbooks can also be revisited in order to promote a better alignment between what is recommended by the Department of Basic Education on the one hand, and what is taught in technology classrooms and with which resources on the other.

6.5.3 Recommendations for future research

Based on the findings and conclusions of this study, I recommend the following studies and topics for future research:

- Case studies investigating the relationship between learners' prior experiences, STEM knowledge, and their engagement in problem structuring, problem solving and leaky cognitive phases.
- Quasi-experimental research to determine the relationship between levels of design expertise and the occurrences of different types of design moves during designing, with the use of linkography.
- Experimental studies measuring the effects of pedagogical interventions on novice designers' generation of orphan, unidirectional and bidirectional moves, as well as how these interventions could support the generation of critical forward and critical backward design moves.
- Multiple case studies investigating the nature of novice designers' socially extended cognition and the factors underpinning effective socially extended design cognition.
- Exploratory quantitative studies focusing on the correlation between different types of physical information sources and the different types of design moves that are generated.
- Content analyses of technology textbooks in relation to curriculum requirements and teachers' lesson planning to determine the sufficiency of information supporting learners' design processes.

- Multiple linkography case studies investigating the co-occurrences of internal and external cognitive processes when novice designers interact with various information sources.
- Follow-up studies on the application value and outcome of linkography as methodological strategy in the context of STEM education practice.

6.6 LIMITATIONS AND CHALLENGES EXPERIENCED DURING THIS STUDY

I identified certain limitations and experienced some challenges during the course of my study. Firstly, the Department of Basic Education does not allow research in schools during normal school hours, or in the first or last school terms or the year. This meant that I had to simulate a natural technology learning environment that gave the participants access to the typical social, conceptual and physical structures to which they were accustomed in their usual classrooms, outside school hours. In order to achieve this, I prepared a TAPS environment, where participating learners had to work collaboratively, giving them access to limited social structures. I furthermore ensured that they were top performing students in Science, Mathematics and Technology in order to ensure that they had access to conceptual structures; and finally, I prepared a design task environment that was rich in available tools and materials for the participants to interact with.

A second potential limitation relates to the concurrent TAPS methodology I selected to employ, as this choice did not allow full access to the internal worlds of the participants. This implies that it was not possible for me to provide evidence of each instantiated design move and subsequently make inferences to account for specific design behaviour. However, in an attempt to compensate for this potential limitation, I engaged in multiple forms of data generation strategies in which I allowed the participants to externally represent their thinking by means of utterances, concurrent sketching, 3D modelling, and written notes. These generated data sources proved to substantiate each other, thereby validating the inferences that I made.

A third potential limitation of this study concerned the sample selection, which resulted in a limited number of participants. However, both the nature of the TAPS methodology (Ericsson & Simon, 1993), as well as the nature of critical realist research (Wynn & Williams, 2012) implies the selection of small sample sizes with the purpose of in-depth studies of specific cases, participants or phenomena. This means that the findings emanating from this study cannot be generalised, however, this was not my purpose as I opted to focus on a small number of novice designers in a specific age group and context. One reason for using small samples in TAPS methodologies can be attributed to the large amount of data that are generated, which in turn has implications for analysis and the reporting of a study. As I however included detailed descriptions of the research process, context and procedures, transferability of the findings to similar contexts may be a possibility.

Furthermore, the samples selected by the technology teachers predominantly comprised of male Grade 8 participants. This was due to the sample selection criteria which compelled the teachers to choose top-performers in science, mathematics and technology in their respective classes, without discriminating according to gender. In addition, the predominantly male samples were also determined by the teachers' knowledge of their learners as they were asked to choose participants that had the ability to communicate effectively, work together as a team, and have displayed above average design skills.

6.7 FINAL CONCLUSION

Children are embedded in environments that contain a variety of information sources that will inevitably influence how they think and what they do. For teachers in the tenets of STEM, it is important to understand the way in which learners interact within the classroom environment, especially in terms of the way that learners access information in social, conceptual and physical environments. The idea that learners think by way of forward and backward design moves is vital to keep in mind because it shows how learners synthesise understanding and design ideas from nothing into something. To this end, the use of linkography implied a novel approach that successfully demonstrated how this strategy can be applied with STEM learners. It further, and more importantly, showed the connection between the different types of thoughts, including unidirectional, bidirectional and critical thoughts, as well as how these types of thoughts arose from learners' interaction within their social, conceptual and physical environments. As such, the study enabled an understanding of *why* learners make certain design choices and generate specific design ideas.

Recommendations stemming from this study touch on training that may benefit STEM teachers in acquiring a certain type of thinking, as well as addressing limitations in the current curriculum and available resources. These limitations could be exploited to assist and further learners’ technology education in general, and their design ability specifically. Understanding the way in which novice designers design will allow the community of scholars in design education to facilitate the necessary processes and provide encouragement as needed. Therefore, with the correct materials, and with encouragement regarding access to prior knowledge and to the relevant constructs, learners can potentially move from the level of being novice designers to being more advanced.

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APPENDIX A – PERMISSION TO CONDUCT RESEARCH

A1 – GDE permission
A2 – Permission from District director
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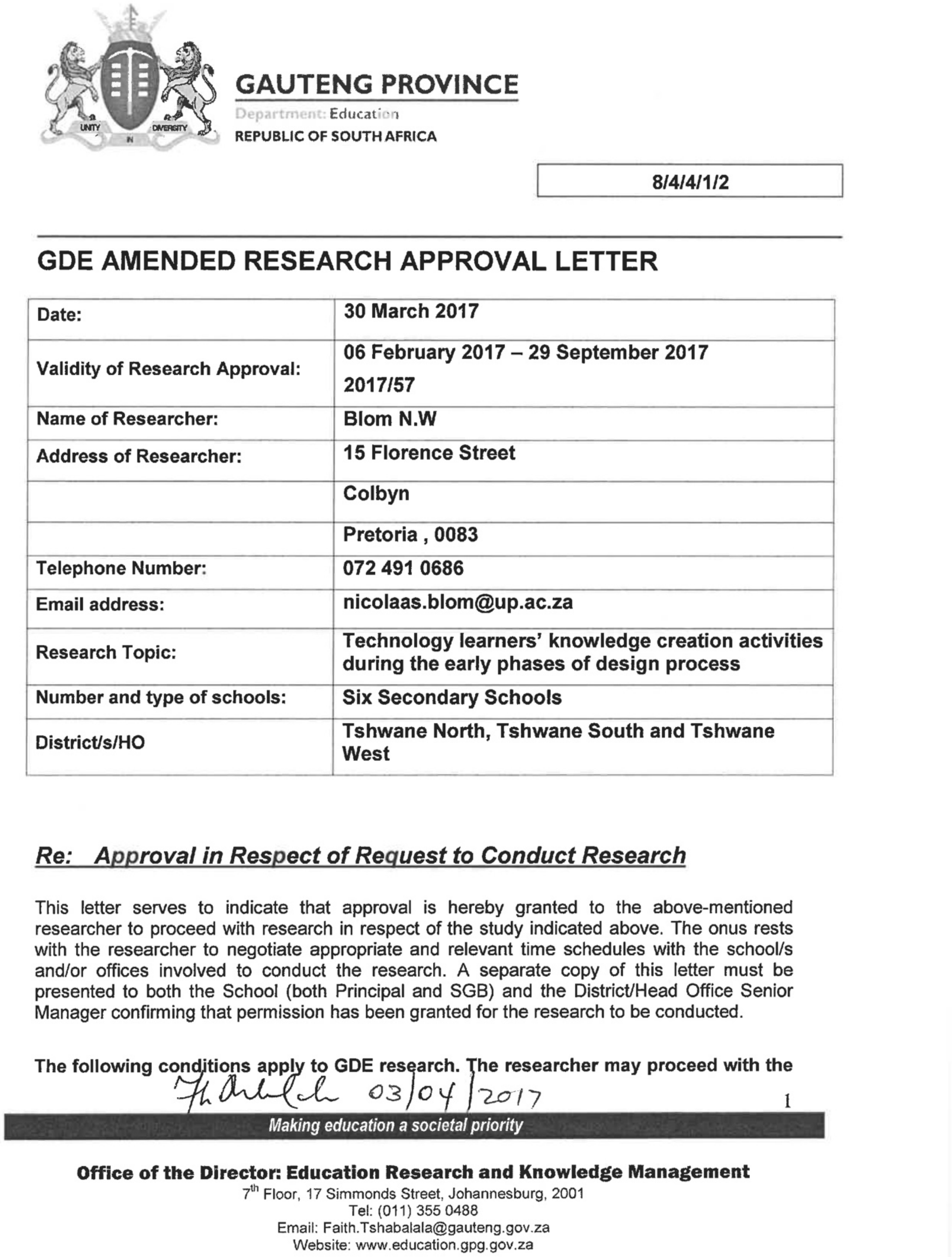
A1 – Gauteng Department of Education Permission



GAUTENG PROVINCE
Department: Education
REPUBLIC OF SOUTH AFRICA

8/4/4/1/2

GDE AMENDED RESEARCH APPROVAL LETTER

Date:	**30 March 2017**
Validity of Research Approval:	**06 February 2017 – 29 September 2017** **2017/57**
Name of Researcher:	**Blom N.W**
Address of Researcher:	**15 Florence Street**
	Colbyn
	Pretoria , 0083
Telephone Number:	**072 491 0686**
Email address:	**nicolaas.blom@up.ac.za**
Research Topic:	**Technology learners' knowledge creation activities during the early phases of design process**
Number and type of schools:	**Six Secondary Schools**
District/s/HO	**Tshwane North, Tshwane South and Tshwane West**

Re: Approval in Respect of Request to Conduct Research

This letter serves to indicate that approval is hereby granted to the above-mentioned researcher to proceed with research in respect of the study indicated above. The onus rests with the researcher to negotiate appropriate and relevant time schedules with the school/s and/or offices involved to conduct the research. A separate copy of this letter must be presented to both the School (both Principal and SGB) and the District/Head Office Senior Manager confirming that permission has been granted for the research to be conducted.

The following conditions apply to GDE research. The researcher may proceed with the

03/04/2017

1. *The District/Head Office Senior Manager/s concerned must be presented with a copy of this letter that would indicate that the said researcher/s has/have been granted permission from the Gauteng Department of Education to conduct the research study.*
2. *The District/Head Office Senior Manager/s must be approached separately, and in writing, for permission to involve District/Head Office Officials in the project.*
3. *A copy of this letter must be forwarded to the school principal and the chairperson of the School Governing Body (SGB) that would indicate that the researcher/s have been granted permission from the Gauteng Department of Education to conduct the research study.*
4. *A letter / document that outlines the purpose of the research and the anticipated outcomes of such research must be made available to the principals, SGBs and District/Head Office Senior Managers of the schools and districts/offices concerned, respectively.*
5. *The Researcher will make every effort obtain the goodwill and co-operation of all the GDE officials, principals, and chairpersons of the SGBs, teachers and learners involved. Persons who offer their co-operation will not receive additional remuneration from the Department while those that opt not to participate will not be penalised in any way.*
6. *Research may only be conducted after school hours so that the normal school programme is not interrupted. The Principal (if at a school) and/or Director (if at a district/head office) must be consulted about an appropriate time when the researcher/s may carry out their research at the sites that they manage.*
7. *Research may only commence from the second week of February and must be concluded before the beginning of the last quarter of the academic year. If incomplete, an amended Research Approval letter may be requested to conduct research in the following year.*
8. *Items 6 and 7 will not apply to any research effort being undertaken on behalf of the GDE. Such research will have been commissioned and be paid for by the Gauteng Department of Education.*
9. *It is the researcher's responsibility to obtain written parental consent of all learners that are expected to participate in the study.*
10. *The researcher is responsible for supplying and utilising his/her own research resources, such as stationery, photocopies, transport, faxes and telephones and should not depend on the goodwill of the institutions and/or the offices visited for supplying such resources.*
11. *The names of the GDE officials, schools, principals, parents, teachers and learners that participate in the study may not appear in the research report without the written consent of each of these individuals and/or organisations.*
12. *On completion of the study the researcher/s must supply the Director: Knowledge Management & Research with one Hard Cover bound and an electronic copy of the research.*
13. *The researcher may be expected to provide short presentations on the purpose, findings and recommendations of his/her research to both GDE officials and the schools concerned.*
14. *Should the researcher have been involved with research at a school and/or a district/head office level, the Director concerned must also be supplied with a brief summary of the purpose, findings and recommendations of the research study.*

The Gauteng Department of Education wishes you well in this important undertaking and looks forward to examining the findings of your research study.

Kind regards

....

Ms Faith Tshabalala
CES: Education Research and Knowledge Management

DATE: 03/04/2017

A2 – Permission from District director

FACULTY OF EDUCATION
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http://www.up.ac.za
06 February 2017

Shirley Molobi
District Director: Tshwane North
Wonderboom Junction
11 Lavender Street
Pretoria

LETTER OF NOTIFICATION: DISTRICT DIRECTOR

Dear Ms Molobi,

I am a PhD student studying through the University of Pretoria and would like to collect data at your school for a research project titled *Technology learners' knowledge creation activities during the early phases of the design process*.

The purpose of this study is to explore how Grade 9 technology learners use various physical and cognitive tools to create knowledge during the early phases of the design process. The researcher will arrange an information session with teachers to explain the nature of this study where they will be invited to participate. This information session will be held in the teachers' usual technology classroom. To participate in this study, a Technology teacher will be invited to complete a questionnaire (15 minutes). I will conduct an interview (30 minutes) with the same teacher. The questionnaire and interview will be completed after school hours in the teachers' technology classroom. These questionnaires and interviews will be used to collect information that might establish technology learners' prior knowledge and their approaches to solving design problems.

Based on this information, the researcher will ask the teacher to further participate in this study by allowing him to video record and observe a 60-minute design problem solving activity of the teachers' technology learners. The video recording will take place during Term 2 or 3, after school hours in the teachers' usual Technology classroom at a time which will suit the school, teachers and the learners. This video recording is necessary because the researcher wants to establish how the different physical and cognitive tools in a technology learning environment influence learners' thought processes. This means that the researcher will examine how Grade 9 learners use different tools (prior knowledge, sketches, 3D models, posters and textbooks) to solve their design problems.

The teacher will be asked to nominate learners (2 groups that consist of 3 learners each) to engage in a design task given by the researcher. This design task will resemble a typical design activity posed in the Technology classroom which is appropriate for Grade 9 learners and which they should complete in 60 minutes. As the research is focused on studying the learners' thinking processes, it will not in any way comment on the teachers' competencies. The teacher will however be present during the video recordings to act as an external information source for the learners during their design tasks. Furthermore, this study will not attempt to evaluate the quality of learners' design solutions or give marks for learners' problem solving abilities, but aims to identify what and how learners are thinking when engaging in design tasks.

The results of this study may be presented at conferences or published in scientific journals. On completion of the study the researcher will supply the Director of Knowledge Management & Research with one electronic copy of the research. If it is required, the researcher will be available to provide short presentations on the purpose, findings and recommendations of his research to both GDE officials and the school concerned.

The teacher, parents and learners will be provided with letters that will elicit their informed consent and the researcher will only commence with data gathering once all these have been granted. The questionnaires, interview transcripts and video recording will only be used for research purposes and the content will remain confidential.

Participation is subject to the Ethics Committee of the Faculty of Education at the University of Pretoria's regulations, and the following will apply:

1. The names of the school and identities of the participants will be treated confidentially, and will not be disclosed.
2. The video recording, questionnaires and interview transcripts will be treated confidentially. Only the researcher (Mr Niekie Blom) and the supervisor (Dr Grietjie Haupt) will have access to the video recordings, questionnaires and the transcribed data.
3. If stills from the video recordings should be used in publications or public presentations, the researcher will ensure that participants' faces and school uniforms will be unrecognizable and censored.
4. Only the researcher (Mr Niekie Blom) will know the real identity of the teacher and learners that agree to participate in the study.
5. Pseudonyms for schools, the teacher and learners will be used in all spoken and written reports.
6. The information provided by the teacher and learners will be used for academic purposes only.
7. Participation in this project is entirely voluntary. Participants have the right to withdraw at any time, and without any prejudice.
8. The teachers and learners will not be exposed to acts of deception at any point in the research study.
9. The teachers and learners will not be placed at risk of any kind.
10. No incentives will be offered to any of the research participants.
11. The videographer involved in the research study will be trained in all matters of ethics, and in particular, confidentiality and anonymity.

The Faculty of Education and the Ethics Committee at the University of Pretoria have approved this study. For any further queries, you are more than welcome to contact the researcher or his supervisor.

Your support in this matter will be appreciated.

Mr. Niekie Blom	Dr. Grietjie Haupt (supervisor)
072 491 0686	(012) 420 5631
nicolaas.blom@up.ac.za	grietjie.haupt@up.ac.za

A3 – Permission from School principal

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06 February 2017

LETTER OF PERMISSION: PRINCIPAL

Dear Principal,

I am a PhD student studying through the University of Pretoria and would like to collect data at your school for a research project titled *Technology learners' knowledge creation activities during the early phases of the design process*.

The purpose of this study is to explore how Grade 9 technology learners use various physical and cognitive tools to create knowledge during the early phases of the design process. The researcher will arrange an information session with teachers to explain the nature of this study where they will be invited to participate. This information session will be held in the teachers' usual technology classroom. To participate in this study, a Technology teacher will be invited to complete a questionnaire (15 minutes). I will conduct an interview (30 minutes) with the same teacher. The questionnaire and interview will be completed after school hours in the teachers' technology classroom. These questionnaires and interviews will be used to collect information that might establish technology learners' prior knowledge and their approaches to solving design problems.

Based on this information, the researcher will ask the teacher to further participate in this study by allowing him to video record and observe a 60-minute design problem solving activity of the teachers' technology learners. The video recording will take place during Term 2 or 3, after school hours in the teachers' usual Technology classroom at a time which will suit the school, teachers and the learners. This video recording is necessary because the researcher wants to establish how the different physical and cognitive tools in a technology learning environment influence learners' thought processes. This means that the researcher will examine how Grade 9 learners use different tools (prior knowledge, sketches, 3D models, posters and textbooks) to solve their design problems.

The teacher will be asked to nominate learners (2 groups that consist of 3 learners each) to engage in a design task given by the researcher. This design task will resemble a typical design activity posed in the Technology classroom which is appropriate for Grade 9 learners and which they should complete in 60 minutes. As the research is focused on studying the learners' thinking processes, it will not in any way comment on the teachers' competencies. The teacher will however be present during the video recordings to act as an external information source for the learners during their design tasks. Furthermore, this study will not attempt to evaluate the quality of learners' design solutions or give marks for learners' problem solving abilities, but aims to identify what and how learners are thinking when engaging in design tasks.

The results of this study may be presented at conferences or published in scientific journals. On completion of the study the researcher will supply the Director of Knowledge Management & Research with one electronic copy of the research.

If it is required, the researcher will be available to provide short presentations on the purpose, findings and recommendations of his research to both GDE officials and the school concerned.

The teacher, parents and learners will be provided with letters that will elicit their informed consent and the researcher will only commence with data gathering once all these have been granted. The questionnaires, interview transcripts and video recording will only be used for research purposes and the content will remain confidential.

Participation is subject to the Ethics Committee of the Faculty of Education at the University of Pretoria's regulations, and the following will apply:

1. The names of the school and identities of the participants will be treated confidentially, and will not be disclosed.
2. The video recording, questionnaires and interview transcripts will be treated confidentially. Only the researcher (Mr Niekie Blom) and the supervisor (Dr Grietjie Haupt) will have access to the video recordings, questionnaires and the transcribed data.
3. If stills from the video recordings should be used in publications or public presentations, the researcher will ensure that participants' faces and school uniforms will be unrecognizable and censored.
4. Only the researcher (Mr Niekie Blom) will know the real identity of the teacher and learners that agree to participate in the study.
5. Pseudonyms for schools, the teacher and learners will be used in all spoken and written reports.
6. The information provided by the teacher and learners will be used for academic purposes only.
7. Participation in this project is entirely voluntary. Participants have the right to withdraw at any time, and without any prejudice.
8. The teachers and learners will not be exposed to acts of deception at any point in the research study.
9. The teachers and learners will not be placed at risk of any kind.
10. No incentives will be offered to any of the research participants.
11. The videographer involved in the research study will be trained in all matters of ethics, and in particular, confidentiality and anonymity.

The Gauteng Department of Education, the Faculty of Education and the Ethics Committee at the University of Pretoria have approved this study. For any further queries, you are more than welcome to contact the researcher or his supervisor.

Your support in this matter will be appreciated.

Mr. Niekie Blom 072 491 0686 nicolaas.blom@up.ac.za	Dr. Grietjie Haupt (supervisor) (012) 420 5631 grietjie.haupt@up.ac.za

Should you agree to participate in the study under the above stated terms, please fill in the details on the next page:

I, _______________________________________(your name only), agree to take part in the research project titled, *Technology learners’ knowledge creation activities during the early phases of the design process*.

……………………………… ……………………………..
Signature Date

A4 – Permission from School Governing Body

FACULTY OF EDUCATION
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06 February 2017

Head of the SGB: (School Name)
Address line 1
Address line 2
Address line 3

LETTER OF NOTIFICATION: SGB

To whom it may concern,

I am a PhD student studying through the University of Pretoria and would like to collect data at your school for a research project titled *Technology learners' knowledge creation activities during the early phases of the design process*.

The purpose of this study is to explore how Grade 8 technology learners use various physical and cognitive tools to create knowledge during the early phases of the design process in a Science, Technology, Engineering and Mathematics (STEM) activity. To participate in this study, a Technology teacher will be invited to complete an interview, which will not last more than 30 minutes. The interview will be conducted after school hours in the teachers' technology classroom. The interview will be used to collect information that might establish learners' prior knowledge and their approaches to solving design problems.

Based on this information, the researcher will ask the teacher to further participate in this study by allowing him to video record and observe a 120-minute design problem solving activity of the teachers' technology learners. The video recording will take place during Term 2 and 3, after school hours in the teachers' usual Technology classroom at a time which will suit the school, teachers and the learners. This video recording is necessary because the researcher wants to establish how the different physical and cognitive tools in a learning environment influence learners' thought processes in a STEM activity. This means that the researcher will examine how Grade 8 learners use different tools (prior knowledge, sketches, 3D models, posters and textbooks) to solve their STEM problems.

The teacher will be asked to nominate learners (2-3 groups that consist of 3 learners each) to engage in a design task given by the researcher. This design task will resemble a typical design activity posed in the Technology classroom which is appropriate for Grade 8 learners and which they should complete in 120 minutes. As the research is focused on studying the learners' thinking processes, it will not in any way comment on the teachers' competencies. The teacher will however be present during the video recordings to act as an external information source for the learners during their STEM tasks.

Furthermore, this study will not attempt to evaluate the quality of learners' work or give marks for learners' problem solving abilities, but aims to identify what and how learners are thinking when engaging in STEM tasks.

The results of this study may be presented at conferences or published in scientific journals. On completion of the study the researcher will supply the Director of Knowledge Management & Research with one electronic copy of the research. If it is required, the researcher will be available to provide short presentations on the purpose, findings and recommendations of his research to both GDE officials and the school concerned.

The teacher, parents and learners will be provided with letters of informed consent and the researcher will only commence with data gathering once all these have been granted. The interview transcripts and video recording will only be used for research purposes and the content will remain confidential.

Participation is subject to the Ethics Committee of the Faculty of Education at the University of Pretoria's regulations, and the following will apply:

1. The names of the school and identities of the participants will be treated confidentially, and will not be disclosed.
2. The video recording, questionnaires and interview transcripts will be treated confidentially. Only the researcher (Mr Niekie Blom) and the supervisor (Dr Grietjie Haupt) will have access to the video recordings, questionnaires and the transcribed data.
3. If stills from the video recordings should be used in publications or public presentations, the researcher will ensure that participants' faces will be unrecognizable and censored.
4. Only the researcher (Mr Niekie Blom) will know the real identity of the teacher and learners that agree to participate in the study.
5. Pseudonyms for schools, the teacher and learners will be used in all spoken and written reports.
6. The information provided by the teacher and learners will be used for academic purposes only.
7. Participation in this project is entirely voluntary. Participants have the right to withdraw at any time, and without any prejudice.
8. The teachers and learners will not be exposed to acts of deception at any point in the research study.
9. The teachers and learners will not be placed at risk of any kind.
10. No incentives will be offered to any of the research participants.
11. The videographer involved in the research study will be equally trained in all matters of ethics, and in particular, confidentiality.

The Gauteng Department of Education, the Faculty of Education and the Ethics Committee at the University of Pretoria have approved this study. For any further queries, you are more than welcome to contact the researcher or his supervisor.

Your support in this matter will be appreciated.

Mr. Niekie Blom	Dr. Grietjie Haupt (supervisor)
072 491 0686	(012) 420 5631
nicolaas.blom@up.ac.za	grietjie.haupt@up.ac.za

APPENDIX B – INFORMED CONSENT AND ASSENT

B1 – Teacher consent form
B2 – Parent consent form
B3 – Learner assent form
B4 – Camera technician confidentially

B1 – Teacher consent form

FACULTY OF EDUCATION
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06 February 2017

LETTER OF INFORMED CONSENT: TEACHER

Dear Teacher,

I am a PhD student studying at the University of Pretoria and would like to collect data at your school for a research project titled *Technology learners' knowledge creation activities during the early phases of the design process*.

The purpose of this study is to explore how Grade 9 technology learners use various physical and cognitive tools to create knowledge during the early phases of the design process. As a technology teacher, you will be invited to complete a questionnaire (15 minutes) and an interview (30 minutes), which will not last more than 45 minutes, in order to establish learners' prior knowledge and how they typically approach design tasks in your technology classroom. These questionnaires and interviews will be completed in during Term 2 and 3 in your technology classroom.

Based on this information, I may ask you to further participate in this study by allowing me to video record and observe a 60-minute design problem solving activity of your technology learners. The video recording will take place during Term 2 or 3, after school hours in your classroom at a time which will suit the you and the learners. This video recording is necessary because I want to establish how the different physical and cognitive tools in a technology learning environment influence learners' thought processes. This means that I will examine how Grade 9 learners use different tools (prior knowledge, sketches, 3D models, posters and textbooks) to solve their design problems.

For the recordings, you will be asked to nominate six learners (2 groups that consist of 3 learners each) to engage in a given design task based on the following criteria: the learners should be able to communicate effectively, work together effectively as a group and should have proficient design skills. I will prepare a design task which will be based on your learners' prior knowledge that will be given to your learners to complete. This design task will resemble a typical design activity posed in the Technology classroom which is appropriate for Grade 9 learners and which they should complete in 60 minutes. The video recording will take place after school hours in the learners' usual Technology classroom at a time which will suit you and the learners.

As the research is focused on studying the learners' thinking processes, it will not in any way comment on your competencies as a teacher. I will also be inviting you to be present in the classroom while I record the learners to act as an external information source if they need to recall prior knowledge. However, I will ask you to only answer their questions and refrain from any teaching activities to guide learners' thinking processes. This study will not attempt to evaluate the quality of learners' design solutions or give marks for learners' problem solving abilities, but aims to identify what and how students are thinking when engaging in design tasks.

The results of this study may be presented at conferences or published in scientific journals. On completion of the study, I will supply the Director of Knowledge Management & Research with one electronic copy of the research. If it is required, I will be available to provide short presentations on the purpose, findings and recommendations of this research to both GDE officials and your school. The video recording will only be used for research purposes and the content will remain confidential.

Participation is subject to the Ethics Committee of the Faculty of Education at the University of Pretoria's regulations, and the following will apply:

1. The names of the school and identities of the participants will be treated confidentially, and will not be disclosed.
2. The video recording, questionnaires and interview transcripts will be treated confidentially. Only the researcher (Mr Niekie Blom) and the supervisor (Dr Grietjie Haupt) will have access to the video recordings, questionnaires and the transcribed data.
3. If stills from the video recordings should be used in publications or public presentations, the researcher will ensure that participants' faces and school uniforms will be unrecognizable and censored.
4. Only the researcher (Mr Niekie Blom) will know the identity of the teacher and learners who agreed to participate in the study.
5. Pseudonyms for schools, the teacher and learners will be used in all spoken and written reports.
6. The information provided by the teacher and learners will be used for academic purposes only.
7. Participation in this project is entirely voluntary. Participants have the right to withdraw at any time, and without any prejudice.
8. The teachers and learners will not be exposed to acts of deception at any point in the research study.
9. The teachers and learners will not be placed at risk of any kind.
10. No incentives will be offered to any of the research participants.
11. The videographer involved in the research study will be trained in all matters of ethics, and in particular, confidentiality and anonymity.

The Faculty of Education and the Ethics Committee at the University of Pretoria have approved this study. For any further queries, you are more than welcome to contact the researcher or his supervisor.

Your support in this matter will be appreciated.

Mr. Niekie Blom	Dr. Grietjie Haupt (supervisor)
072 491 0686	(012) 420 5631
nicolaas.blom@up.ac.za	grietjie.haupt@up.ac.za

Should you agree to participate in the study under the above stated terms, please fill in the details on the next page:

I, ____(your name only), agree to take part in the research project titled, *Technology learners' knowledge creation activities during the early phases of the design process*.

……………………………… ……………………………..
Signature Date

B2 – Parent consent form

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06 February 2017

LETTER OF INFORMED CONSENT: PARENTS

Dear Parent(s)/Guardian(s),

I am a PhD student studying at the University of Pretoria and would like to collect data at your child's school for a research project titled *Technology learners' knowledge creation activities during the early phases of the design process*.

The purpose of this study is to explore how Grade 9 technology learners use various physical and cognitive tools to create knowledge during the early phases of the design process. Your child was selected by their technology teacher as someone who demonstrates very good designing abilities. I would appreciate it if you will allow me to video record and observe a 60-minute design problem solving activity of your child. The video recording will take place during Term 2 or 3, after school hours in your child's usual Technology classroom at a time which will suit you, the school, the teacher and the learners. This video recording is necessary because I want to establish how the different physical and cognitive tools in a technology learning environment influence learners' thought processes. This means that I will examine how Grade 9 learners use different tools (prior knowledge, sketches, 3D models, posters and textbooks) to solve their design problems.

In this study, I will prepare a design task which will be based on your child's prior learning in technology, which I will ask them to complete in a design group (2 groups that consist of 3 learners each). The design task that I will give to your child will resemble a typical design activity posed in the Technology classroom which is appropriate for Grade 9 learners and which they should complete in 60 minutes. As the research is focused on studying the learners' thinking processes, it will not in any way comment on the teachers' competencies. The teacher will be present in the classroom while I record the learners. However, the teacher will not help the learners, but only answer their questions if they have any. Furthermore, this study will not attempt to evaluate the quality of learners' design solutions or give marks for learners' problem solving abilities, but aims to identify what and how the learners are thinking when engaging in their design tasks.

The results of this study may be presented at conferences or published in scientific journals. On completion of the study, I will supply the Director of Knowledge Management & Research at the Gauteng Department of Education with one electronic copy of the research. If it is required, I will be available to provide short presentations on the purpose, findings and recommendations of this research to both GDE officials and your school. The video recording will only be used for research purposes and the content will remain confidential.

Participation is subject to the Ethics Committee of the Faculty of Education at the University of Pretoria's regulations, and the following will apply:

1. The names of the school and identities of the participants will be treated confidentially, and will not be disclosed.
2. The video recording, questionnaires and interview transcripts will be treated confidentially. Only the researcher (Mr Niekie Blom) and the supervisor (Dr Grietjie Haupt) will have access to the video recordings, questionnaires and the transcribed data.
3. If stills from the video recordings should be used in publications or public presentations, the researcher will ensure that participants' faces and school uniforms will be unrecognizable and censored.
4. Only the researcher (Mr Niekie Blom) will know the identity of the teacher and learners who agreed to participate in the study.
5. Pseudonyms for schools, the teacher and learners will be used in all spoken and written reports.
6. The information provided by the teacher and learners will be used for academic purposes only.
7. Participation in this project is entirely voluntary. Participants have the right to withdraw at any time, and without any prejudice.
8. The teachers and learners will not be exposed to acts of deception at any point in the research study.
9. The teachers and learners will not be placed at risk of any kind.
10. No incentives will be offered to any of the research participants.
11. The videographer involved in the research study will be trained in all matters of ethics, and in particular, confidentiality and anonymity.

The Faculty of Education and the Ethics Committee at the University of Pretoria have approved this study. For any further queries, you are more than welcome to contact the researcher or his supervisor.

Your support in this matter will be appreciated.

Mr. Niekie Blom	Dr. Grietjie Haupt (supervisor)
072 491 0686	(012) 420 5631
nicolaas.blom@up.ac.za	grietjie.haupt@up.ac.za

Should you agree to participate in the study under the above stated terms, please fill in the details below:

I, ____(your name only), agree that my child may take part in the research project titled, *Technology learners' knowledge creation activities during the early phases of the design process.*

……………………………… ……………………………..
Signature Date

B3 – Learner assent form

FACULTY OF EDUCATION
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06 February 2017

LETTER OF INFORMED ASSENT: LEARNERS

Dear Learner

Why am I here?

Sometimes when we want to find out something, we ask people to join something called a project. What you are taught in your class and how your teacher teaches it is often based on research. To continue to improve on what you are taught and how you are taught, there are research projects to look at what happens in a typical classroom. This is such a research project. In this project I shall ask you to do an activity which is focused on your own development and learning. Before I ask you to be part of this study, I want to tell you more about it first.

This project will give me a chance to look at different ways that you can use to solve design and technology problems. This will help me to train future technology teachers on how to better teach design problem solving.

What will happen to me?

If you will be part of my study, you will be video recorded after school in your usual Technology classroom during a 60 minute design and technology activity, while your teacher and I will be in the classroom. Your teacher will ask you to complete a fun activity in which you will investigate and solve a problem while speaking about your thoughts. The activity will only take 60 minutes and you can take a break if you are feeling tired. There will be no right or wrong answers, only what you feel is best. You can ask your teacher to remind you of previous work that you have done as well. I will also ask you to try and tell me what you are thinking during the activity, so that other people may hear what you have to say, but they will not know who you are. I will not use your name on the recording or in any report. The recording will only be used for me to check what you have said (like notes), so there is no need to worry about what others may think about you or how you might look or act in the class, since the recording will not be shown to anyone (except your teacher, the camera person and my teacher). If you do not want to say anything about the activity, you do not need to.

Will the project help me?

This project might help you to improve your thinking skills during design projects, but this project is a bit like cleaning up a river, building houses in poor areas, or protecting rhinos; it will not necessarily help you immediately, but it may help to improve how technology is taught in future. I do hope that this project will be fun and help you to feel good about yourself and learn more about what you can do in school.

What if I have any questions?

You can ask your teacher any questions you have about this project. If you have questions later that you do not think of now you can phone Mr Niekie Blom at 012 420 2771, or you can ask him next time you see him at school.

Do my parents/guardians know about this project?

This project was explained to your parents/guardians in a letter, and they agreed that you could be part of the project if you want to. You can talk this over with them before you decide if you want to be in this project or not.

Do I have to be in the project?

You do not have to be in this project if you do not want to. No one will be upset if you do not want to participate. You will not lose any marks for technology if you do not participate. If you do not want to be in the project, you just have to tell us. You can say yes or no and if you change your mind later, you do not have to be part of the project anymore. It is up to you.

Writing your name on this page means that you agree to be in the project and that you know what will happen when we do the project. If you decide to quit the project at any time, all you have to do is tell me or your teacher.

……………………………… ………………………………………….
Signature of the learner Date

……………………………… ………………………………………….
Signature of the researcher Date

……………………………... ………………………………………….
Signature of the supervisor Date

B4 – Camera technician confidentially

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06 February 2017

CAMERA TECHNICIAN CONFIDENTIALITY AGREEMENT

Study: Technology learners' knowledge creation activities during the early phases of the design process.

I, ________________________________ (name of research assistant), agree to assist ***Nicolaas Willem Blom*** (name of primary investigator), with this study by recording sessions with participants on video.

I agree that I will:
- keep all research information shared with me confidential and not discuss or share the information in any form or format (e.g. disks, tapes,) with anyone other than the primary investigator of this study; and
- keep all research information in any form or format (e.g. disks, tapes, transcripts) secure while it is in my possession.

This includes:
- to give all research information in any form or format (e.g. disks, tapes, transcripts) to the primary investigator when I have completed the video recordings; and
- to erase or destroy all research information in any form or format that is not returnable to the primary investigator (e.g. information stored on my video recorder hard drive) upon completion of the recording sessions.

……………………………… ………………………………
Signature of the camera technician Date

……………………………… ………………………………
Signature of the researcher Date

……………………………… ………………………………
Signature of the supervisor Date

APPENDIX C – DATA GENERATION PROCEDURES

C1 – The STEM task
C2 – List of tools and materials in the design task environment
C3 – Teacher interviews

C1 – The STEM task

Group:

Participant:

PROBLEM CONTEXT

Food vendors are situated at most of the taxi ranks in South Africa. People can buy a meal after a long day of work before catching a taxi and heading home. Food vendors usually sell food to customers in plastic polystyrene containers. However, these containers do not retain the heat of the food inside the container for the trip home. Also, these containers are not easily recyclable because it is contaminated with food and difficult to clean because it is so porous, and therefore does not support sustainable use of the country's resources.

One of the most popular dishes served by the street vendors in South Africa is 'pap and meat'. The pap is maize meal porridge, which is usually made thick enough to eat with your fingers. There are also many different meat options to choose from, including, chicken, beef, mutton or fish. The meat is served in a tasty gravy or 'chakalaka'. As a take away meal bought from the street vendors, the pap and the meat is often served separately in a polystyrene container.

Fig. 1: A portion of pap and meat in a polystyrene container

DESIGN OPPORTUNITY

Design a recyclable heat retaining food container that will ensure that the pap and meat dish placed therein would retain its heat for at least one hour.

REQUIREMENTS

1. The container should be able to keep the food hot for one hour
2. The container should be made from biodegradable materials
3. The container should be comfortable to carry as a take away container
4. The container should hold the food so that it does not spill or leak.

5. The container should be able to contain food and withstand forces in a crowded transport environment
6. The container should be able to contain 1.1kg of food.

CONSTRAINTS

- Only recyclable materials should be used

INSTRUCTIONS

In this problem solving task, you will be working in a group. You are required to design and make a recyclable heat retaining container to be used by street vendors as a take away container for pap and meat. Throughout the design task you may use information from your memory, textbook and workbook if you need it. You may ask anyone in the room for information. You are also allowed to highlight, make notes and draw sketches on all the pictures and notes given to you.

1. Consider the environment in which the pap and meat is sold and eaten. Discuss the following questions: (20 minutes).

- What is the problem(s) that needs to be solved? How can we solve it?
- Who are we designing for?
- Where will the food container be used?
- When will the food container be used?
- How will the food container be used?
- How big does the food container need to be?
- What materials and tools can be used to make the design?
- What should the food container be able to do?

2. Write a design brief, the specifications and the constraints for your design solutions (20 minutes).

3. Make a number of annotated freehand sketches of possible solutions for the street traders. Suggest at least two to three different designs that will be able to solve the problem (30 minutes).

4. Evaluate your designs and choose the best possible design. Make a 3D model of your chosen design solution from the given materials (50 minutes).

STREET TRADING ENVIRONMENT

Fig. 2: Street vendor selling pap and meat

Fig. 3: Selling area for pap and meat

Fig. 4: Inside a taxi

Fig. 5: Street market at a taxi rank

DIFFERENT FOOD PACKAGING

Fig. 6: Separated container

Fig. 7: Container that folds into a plate

Fig. 8: Carry and foldable takeaway

Fig. 9: Food paper box

Fig. 10: Separated hamburger packaging

Fig. 11: Compostable bowls

Fig. 12: Carrier take away holder

PACKAGING SHAPES

Fig. 13: Rectuangular prisms

Fig. 14: Foldable boxes

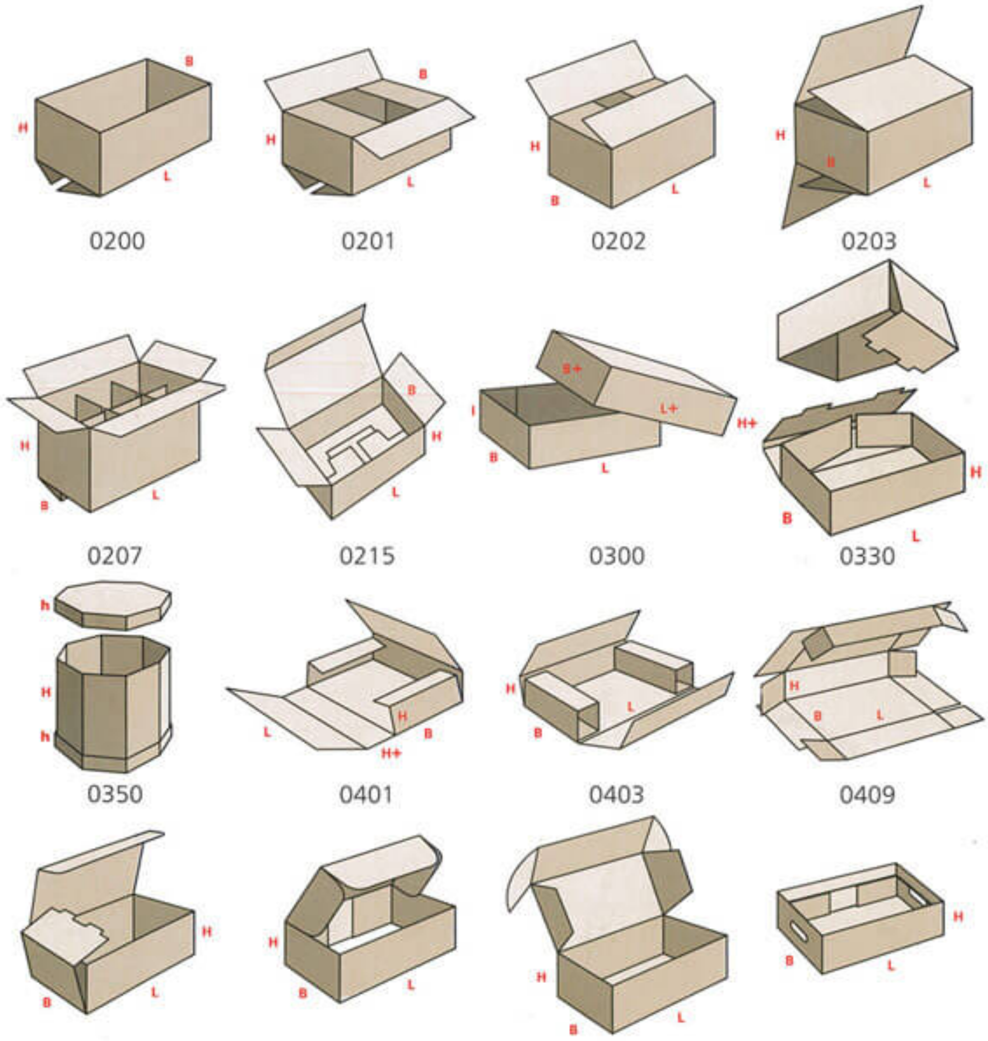
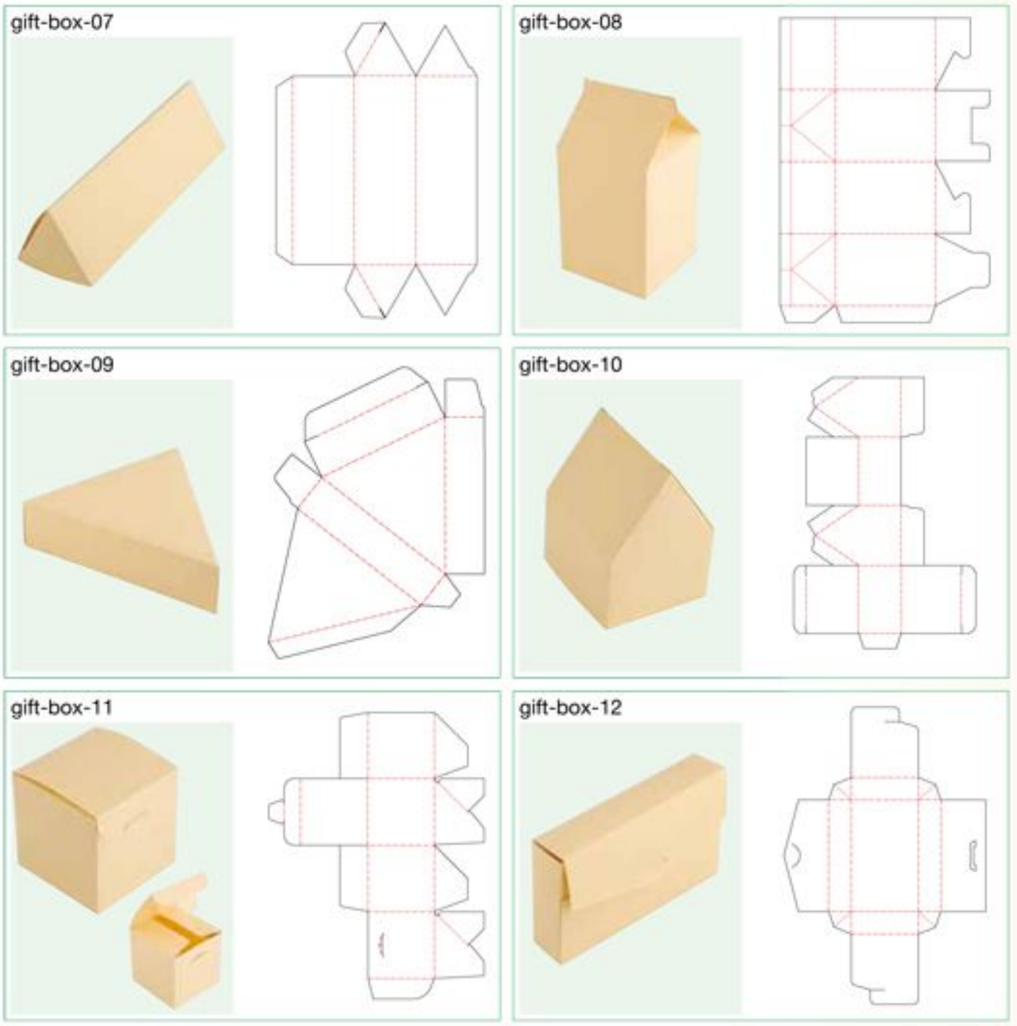


Fig. 15: Various gift boxes



gift-box-07

gift-box-08

gift-box-09

gift-box-10

gift-box-11

gift-box-12

Fig. 16: Heat insulators

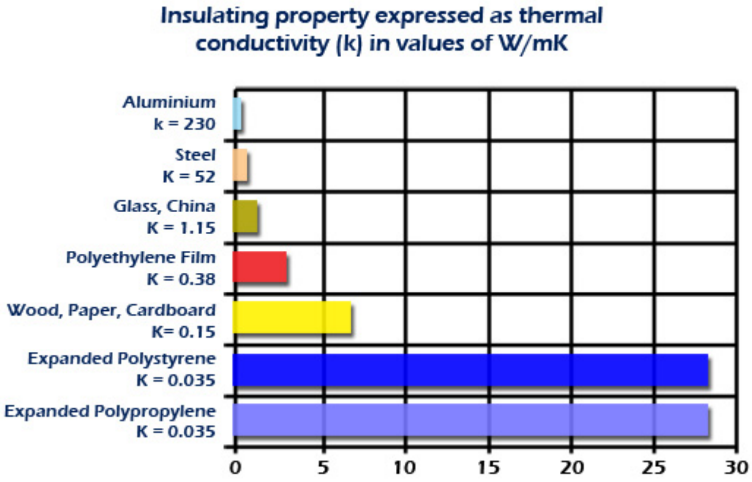
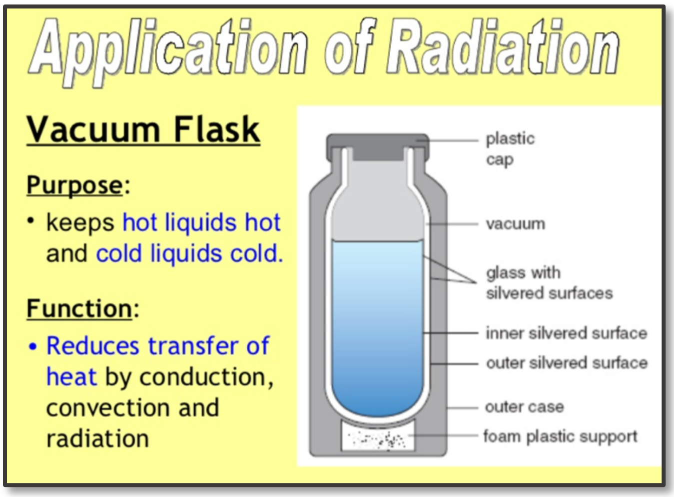


Fig. 17: Practical application of materials for radiation



Application of Radiation

Vacuum Flask

Purpose:

- keeps hot liquids hot and cold liquids cold.

Function:

- Reduces transfer of heat by conduction, convection and radiation

Fig. 18: Thermally insulated lunchbox

C2 – List of tools and materials in the design task environment

STATIONARY	QTY	TOOLS AND MATERIALS	QTY
HB pencils	3	Glue sticks	2
Pencil sharpener	1	Clear glue	1
Coloured pencils	12	Wood glue	1
Coloured pens	5	Prestic	1
Coloured felt pens	5	Insulation tape	1
Highlighters`	5	Cello tape	1
Post it notes	1	Masking tape	1
Copy paper A4	10	Cable ties	8
Copy paper A3	3	String	1
Paper clips	1 box	Stapler	1
Elastic bands	10	Paper fasteners (round head)	1 box
Cutting mat	1	Metal clips (clampers)	3
Scissors	3	Medium Fold back clips	1 box
Safety rulers	3	Large Fold over clips	3
Exam Pad	1	Ice cream sticks	50
A4 cardboards	5	Plastic slide binders	5
Stickers	1 sheet	Utility knives	2
Foam sheets	3	Modelling clay	1
Felt sheets	2	Kebab sticks	16
Coloured cardboard sheets	5	Roll brown paper wrapping	1
Double folio sheets	5	Toothpicks	1 box
PACKAGING	**QTY**	‘Checkers’ shopping bags	2
Small corrugated cardboard net	1	Dish cloth	1
Triangular prism	1	Triangular long cardboard with rope	1
Black food parcel box	1	Roll of Aluminum foil	1
Polystyrene sheet	1	Plastic forks	2
Plastic separated plate	1	Kitchen scale	1
Round plastic salad bowl	1	Calculator	1
Round foil container with plastic lid	1		
Foil tray	1		
Foil container with lid (paper and foil)	1		
Styrofoam container	1		
Brown paper bags	4		
Ice cream cylinder packaging	2		
Mac Donald’s happy meal packaging	1		

C3 – Teacher interviews

APPENDIX D – DATA ANALYSIS PROCEDURES

D1 – Coding framework
D2 – Qualitative codebook
D3 – Macro level analysis
D4 – Meso level analysis
D5 – Micro level analysis

D1 – Coding framework

No	LAYER 1: PARTICIPANT // EMPIRICAL LEVEL	
1	Participant identification	Identifying the generator of the utterance/sketch/written note/3D model
	LAYER 2: DESIGN MOVE AND LINKS // EMPIRICAL LEVEL	
2	Design move	A design move is defined as “a step, an act, an operation which transforms the design situation relative to the state in which it was prior to that move” (Goldschmidt, 1995, p. 195). This is akin to a move in chess. According to an extended cogntive viewpoint, moves represents the different mediating states in an extended problem solving space. I only viewed utterances that were relevant to the design problem space. Any other moves, including, space management moves, or off-topic talk were not coded as design moves. I also did not code utterances that repeated the same information as a previous utterance, because that implied a move that was already present in the design space.
3	Backward links	All the connections made in a Linkograph are backlinks, as the moves in question link to posterior moves. Moves can also have forelinks to consecutive moves. There is a difference between forelinks and backlinks. Whereas backlinks can be determined at the time the move is made, forelinks can only be established only at the end of a recorded design process. Links were made between design moves when one or more of the following criteria were met: • The participants related directly to earlier thoughts in the protocol, • There were visible hand gestures, sketching, 3D modelling, or writing relating to earlier thoughts, • There were structural, functional or behavioural (semantic) similarities between thoughts, and • 4) Design moves occurred in serial and were within the same chain of thought.
	LAYER 3: MODE OF OUTPUT // EMPIRICAL LEVEL	
4	Talking	Activity is evidenced only in verbal utterances
5	Writing	Activity is evidenced in verbal utterances + written notes
6	Sketching	Activity is evidenced in verbal utterances + design sketches
7	3D Modelling	Activity is evidenced in verbal utterances + 3D modelling activities
	LAYER 4: COGNITIVE PHASE // ACTUAL LEVEL	
8	Problem structuring	Understanding the problem in terms of the needs of users, the environment of the object, the design requirements, design goals, the design constraints and the required function of the designed product. Understanding the required knowledge to solve the design problem: For example, understanding concepts of heat transfer, biodegradable materials, recyclable materials, etc.
9	Problem solving	Utterances that shows how the participants generate, clarify, develop or evaluate emerging or existing solutions.
10	Leaky phase	Utterances based on proposing and developing design solutions while simultaneously making utterances based on finding missing information about the people involved, the design objectives, the problem context or knowledge needed to address the design problem

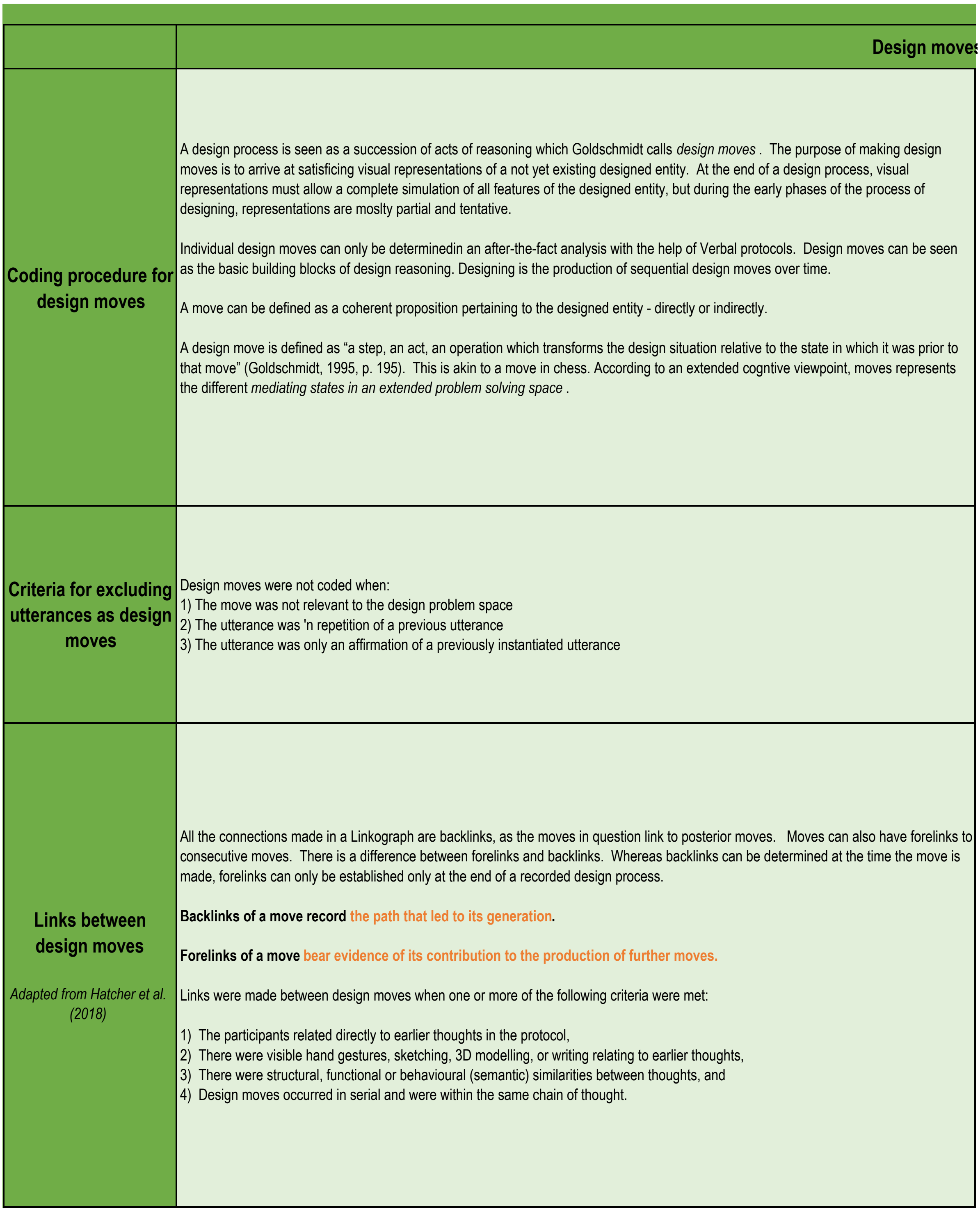
	LAYER 5: DESIGN PROCESS ACTIVITY // ACTUAL LEVEL	
	Design process activity (DoBE, 2011)	Investigating the problem
		Investigating the context
		Investigating materials
		Investigating appearance
		Investigating size
		Investigating weight
		Investigating shape
		Investigating existing products
		Formulating constraints and requirements
		Generating solutions
		Clarifying solution
		Developing solution
		Modifying solution
		Evaluating solution
	LAYER 6: PROBLEM SOLVING GOAL // ACTUAL LEVEL	
	Problem solving goal (Young, 2014)	Understanding problem
		Understanding context
		Understanding materials
		Understanding weight
		Understanding size
		Understanding appearance
		Understanding shape
		Finding suitable solutions
		Finding suitable materials
		Finding suitable size
		Finding suitable shape
		Committing to a solution
		Realising solution
		Developing committed solution
	LAYER 7: DESIGN INTENTIONS // REAL LEVEL	
	Design intentions	Contain food
		Biodegradable
		Convenience
		Retain heat
		Economic
		Reuse
		Separate food
		Insulate heat
		Recyclable
		Protect food
		Strength
		Hygienic
		Aesthetics
		Inclusivity
		Stability
		Foldability
	LAYER 8: EXTERNAL SOURCE INTERACTION // REAL LEVEL	
	Problem statement instructions	Utterance made while pointing/gazing/indicating at Problem statement instructions
	Figure	Utterance made while pointing/gazing/indicating at figure
	Drawing	Utterance made while pointing/gazing/indicating at drawing
	Written note	Utterance made while pointing/gazing/indicating at written note
	Physical object	Utterance made while pointing/gazing/indicating at physical object
	Tool	Utterance made while pointing/gazing/indicating at tool
	Textbook/Class notes	Utterance made while pointing/gazing/indicating at class notes/textbook
	3D modelling	Utterance made while pointing/gazing/indicating at 3D model

	Teacher	Utterance made while pointing/gazing/indicating at teacher

	LAYER 9: INTERNAL SOURCE INTERACTION // REAL LEVEL	
	Scientific knowledge	Utterance made while recalling/remembering/applying scientific knowledge
	Technological knowledge	Utterance made while recalling/remembering/applying technological knowledge
	Mathematics knowledge	Utterance made while recalling/remembering/applying mathematical knowledge
	Previous experience	Utterance made while recalling/remembering/applying previous experience
	Previous instance	Utterance made while recalling/remembering/applying previous instance
	LAYER 10: PROBLEM SOLVING OPERATIONS // ACTUAL LEVEL	
	Add	The basic operation of putting something into the problem space with some degree of commitment
	Propose	Indicates that an idea is being entertained but is not yet committed to the problem space.
	Evaluate	Means that the statement is an explicit evaluating of a previous statement or design component in the problem space.
	Comment	By and large, the reporting of an activity - rather than the execution of it. They generally occur with monitoring statements. Often they involve a learners' explaining the action just taken or making some remarks that, while not directly related to the learners' progress, are nonetheless illuminating.
	Modify	A statement that deletes or alters an exisiting idea or element that is already part of the problem space. It is sometimes difficult to distinguish between 'add' and 'modify'; between an old idea's being modified and a new one's being added.
	Elaborate	Expands an existing idea or element
	Justify	Offers a rationale for adding to, modifying, or elaborating on ideas or elements in the problem space.
	Read	Involves the participants' reading of any material in the task environment such as the design task, workbooks, or external sources of information.
	Qualify	Statements used to hedge or further qualify the previous statement.
	Request	Any request made by participants to me or the teacher in asking questions or making suggestions.
	Repeat	The application of the same operator to the same content.
	LAYER 11: DESIGN CHOICE EVENTS // ACTUAL LEVEL	
	Conceptual	What the container will do
	Technical	How the container will work
	Aesthetic	How the container will look like
	Safety	How safety is ensured
	Material	What is it made from
	Constructional	How it fits together
	Marketing	Who is it for
	LAYER 12: MECHANISMS // REAL LEVEL	
	Perceiving affordance	Inspecting, looking at, attending to, referring to external information source, tool or representation *(seeing possibilities)*
	Perception-action	Inspecting, looking at, attending to, referring to external information source, tool or representation and following with an action *(acting on possibilities)*
	Intention-attention	Participants look for useful information by paying attention to physical aids, and use information to address their intentional behaviour,

D2 – Qualitative Codebook

An example of my qualitative codebook is provided as hard copy. The full codebook can be accessed on the CD-rom



	Design moves
Coding procedure for design moves	A design process is seen as a succession of acts of reasoning which Goldschmidt calls *design moves* . The purpose of making design moves is to arrive at satisficing visual representations of a not yet existing designed entity. At the end of a design process, visual representations must allow a complete simulation of all features of the designed entity, but during the early phases of the process of designing, representations are moslty partial and tentative. Individual design moves can only be determinedin an after-the-fact analysis with the help of Verbal protocols. Design moves can be seen as the basic building blocks of design reasoning. Designing is the production of sequential design moves over time. A move can be defined as a coherent proposition pertaining to the designed entity - directly or indirectly. A design move is defined as "a step, an act, an operation which transforms the design situation relative to the state in which it was prior to that move" (Goldschmidt, 1995, p. 195). This is akin to a move in chess. According to an extended cogntive viewpoint, moves represents the different *mediating states in an extended problem solving space* .
Criteria for excluding utterances as design moves	Design moves were not coded when: 1) The move was not relevant to the design problem space 2) The utterance was 'n repetition of a previous utterance 3) The utterance was only an affirmation of a previously instantiated utterance
Links between design moves *Adapted from Hatcher et al. (2018)*	All the connections made in a Linkograph are backlinks, as the moves in question link to posterior moves. Moves can also have forelinks to consecutive moves. There is a difference between forelinks and backlinks. Whereas backlinks can be determined at the time the move is made, forelinks can only be established only at the end of a recorded design process. **Backlinks of a move record the path that led to its generation.** **Forelinks of a move bear evidence of its contribution to the production of further moves.** Links were made between design moves when one or more of the following criteria were met: 1) The participants related directly to earlier thoughts in the protocol, 2) There were visible hand gestures, sketching, 3D modelling, or writing relating to earlier thoughts, 3) There were structural, functional or behavioural (semantic) similarities between thoughts, and 4) Design moves occurred in serial and were within the same chain of thought.

Cognitive phases	
Problem structuring	Utterances based on finding missing information about the people involved, the design objectives, the problem context or knowledge needed to address the design problem. Problem structuring is the process of retrieving information from long-term memory and external memory and using it to construct the problem space, i.e. to specify start states, goal states, operators and evaluation functions. Problem structuring as compared to problem solving relies heavily on the client and design brief as source of information, considers information at a higher level of abstraction, makes fewer commitments to decisions, and involves a higher percentage of add and propose operators. One particularly interesting strategy for problem structuring is reversing the direction of the transformation function.
Problem solving	Utterances based on applying information about to propose and develop design solutions Preliminary design is a phase where alternative solutions are generated and explored. Alternative solutions are neither numerous nor fully developed when generated. They emerge through incremental transformations of a few kernel ideas. These kernel ideas are images, fragments of solutions, etc., to other problems which the designer has encountered at some point in his life experience. Since these 'solutions' are solutions to other problems which are being mapped on to the current problem, they are, not surprisingly, always out of context or in someway inappropriate and need to be modified to constitute solutions to the present problem.
Leaky phase	Utterances based on applying information about to propose and develop design solutions while simultaneously making utterances based on finding missing information about the people involved, the design objectives, the problem context or knowledge needed to address the design problem

D3 – Macro level analysis

An example of the macro-level analysis is provided in hard copy. The full macro-level analysis can be accessed on the CD-ROM

Episode	Time	Overview	Intentions/thought content	Information sources	Significant Events
1	09:04 - 12:15	**Examining existing ideas** Participants use Photographs of existing products to find or eliminate design ideas. As they evaluate the existing products, design intentions emerge, like strenght emerge. Prior to the episode, particpants were managing themselves and discussed how plastic could be used to make the container. However, the episode starts when P1 asks a question, what will work in the taxi? This results in a process where participants critiques eight existing products. Of these eight products, five are seen as suitable ideas to develop	Foil (11); Separators (17); Economic (20); Strength (7, 8, 21); Insulation (9, 16, 19)	Figure 6-10, 13 & 18	1) Searching for ideas throught existing ideas (#1-7) 2) Understanding Insulation material 3) Searching for ideas throught existing ideas (#8-9)
2	13:11 - 15:46	**The use of materials** In this episode the participants explore a range of materials that they can use in their designed product. They mainly use Figure 16 to discuss the suitablility of materials. P1 is writing a list of the discussed materials. At one point P2 asks whether the materials are biodegradable, which leads the particpants to eliminate unsuitable materials. P3 also suggests making something like a flask, illustrated in Fig. 17. After eliminating the materials, they note that they can only use cardboard.	General and biodegradable materials (22-32; 34)	Figure 16; Writing; Technological knowledge of biodegradable materials; Figure 17	1) Understanding and searching for biodegradable materials with insulation properties
3	15:48 - 18:25	**Battling with biodegradeable materials and choosing a shape** After realising they only have cardboard to work with P2 suggests that they should consider making their design in a triangular shape. P3 recognises a triangular prism and stating that they could put the food on the inside, after which P2 develops the idea to make it bigger and use cardboard to construct it. They also realise that they don't yet have isolation material, that is biodegradable, to keep the heat inside. Once the particpants see the material as a stumbling block and cannot continue with their idea of a triangular shape, P1 starts to look for ideas in class notes. While looking at the photographs of existing products, P2 suggests that they could develop the idea of Fig. 12, based on its triangular shape, which P3 comments need to be strenghend. P1 reflects back on their use of a triangular shape by asking if they will use a triangular shape. He then writes it down in a list	Triangular shape (37) Carry easily (47-48) Heat insulation (43)	Figure 9; Triangular prism; Class notes; Writing	1) Choosing a triangular shape 2) Searching for ideas with triangular shapes (#11-12)

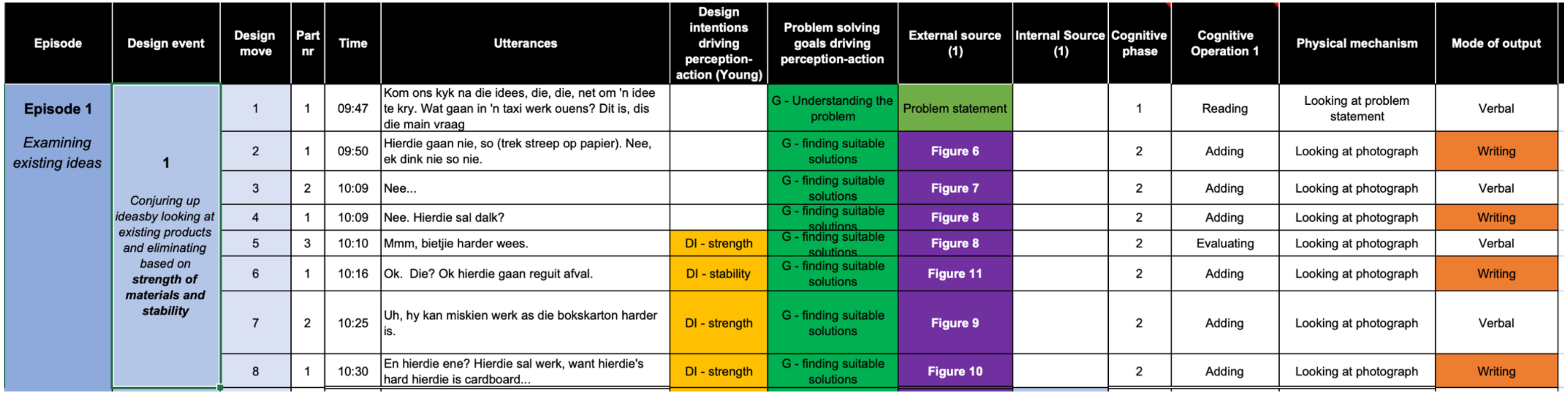
D4 – Meso level analysis

An example of the meso-level analysis is provided in hard copy. The full meso-level analysis can be accessed on the CD-ROM

Episode	Significant event	Time	Detailed context of utterances	Content of thoughts	Internal sources and Intentions	External information sources	Cognitive activities	External/Physical activities	Social activities
Episode 1 *Examining existing ideas*	**1** *Searching and conjuring ideas from existing products*	09:47 - 10:38	During the first event the participants were guided by P1, who asked a question: *What would work in the taxi?* This question leads the participants to conjure up seven ideas by looking at photographs (Figures 6-11) of existing ideas in this event. While they are looking at the existing ideas, they evaluate each existing ideas. At idea #3, it is clear that P3 used 'strength of material' intention to evaluate idea #3, P1 use stability intention to evaluate idea #4 and P1 and P2 use 'strength of material intentions to evaluate ideas #5-6. In the final move, P1 justifies idea #6 because cardboard is hard and would therefore be strong enough in a taxi..	Strength (5, 7, 8) Strength of material (7,8) Stability (6)	**R** - Strength **Di** - Stability	PS Fig 6 Fig 7 Fig 8 Fig 11 Fig 9 Fig 10	**Proposing** ideas #1-6 **Suggesting** change of existing idea (to make harder) **Evaluating** ideas from photographs based on an intention of strength of materials	**Looking and pointing** at photographs to conjure, evaluate and justify ideas	The question asked by P1 seems about what would work in a Taxi, seems to guide all the participants to respond by thinking of ideas that would be hard and stable enough in a taxi. This suggests their intentions for the the foodcontainer to be hard and stable.
	2 *Understanding insulation material*	10:38 - 10:51	After proposing and evaluating ideas in event 1, P2 asks for a material that can serve as insulation for idea #6. This seems to point out the teams intention to keep the heat of the food inside the container, so that the food would remain hot for longer. This also suggest that they used scientific knowledge that insulation prevents heat transfer from occuring. To P2's question of finding insulation for idea #6, P1 proposes the use of plastic which could be wrapped around the outside of a container. P2 rejects this idea by stating that plastic will not insulate the container and propose aluminium foil instead - To which P3 elaborates that it should be on the inside of the container (Figure 10), not wrapped around like P1 suggested.	Need for insulation material (9) Keeping heat inside the container (11) Insulation material - foil (11)	**Science knowledge** (Concept - insulation) **Technological knowledge** (Material properties)	Fig 10	**Adding** insulation material to the problem space **Proposing** the use of plastic on the outside of the container **Evaluating** the use of plastic and proposing foil instead. **Elaborating** that foil should be used on the inside of the container	* **Looking at Fig.10** to evaluate idea #6 * **Looking at Fig 10 and Gesturing** how plastic can be wrapped over container * **Looking at each other** to evaluate, propose insulation material * **Looking at each other** to elaborate on using insulation material	The question asked by P2 to find something that could insulate the heat provided opportunity for P1 to respond with using plastic on the outside of the container. P2 did not agree with this and rejected plastic as an insulating material and rather suggested alluminium foil. P3 then elaborated that the foil should be used on the inside of the container to insulate the heat. The team then carries on, which signifies agreement.
	3 *Searching for ideas with existing products*	10:51 - 13:11	After briefly proposing and elaborating on the use of aluminium foil on the inside of the container, P1 summarises ideas #3,5,6 which they discussed during event 1 as suitable for development. He then starts to conjure up another design ideas #7 by looking at another photograph (Figure 14) of a container with separators. P3 then further develops this idea by acknowledging that it has separators and suggesting that it should be wrapped in plastic with an insulating material on the inside of the container - seemingly from prior design moves (10&12). After a while, P2 proposes a new idea #8 when looking at Figure 18. It seems as if the fact that he mentioned that the container should be wrapped in plastic and the insulator on the inside (16), led him to recognise the making a food "bag" with an insulator on the inside. He subsequently proposes the use of separators on the inside to separate the pap and the meat. Based on this, P1 elaborated on P2's idea by suggesting that they could make a container inside the food bag, making the food bag the insulator. However, P1 evaluates his own idea, by thinking of the end-users of the container, stating that it would be too expensive. This suggests an economic intention. P2 subsequently elaborate that it is for this reason that they should use materials like cardboard or wood, indicating that they have not yet commited to a material. P2 further evaluates the idea by stating that using more than two materials would be able to withstand impacts in a taxi.	Separation of pap and meat (**15**) Keeping heat inside the container Insulation material (16) Economic for users (20) Strength - two layers (21) Materials - Cardboard (21) Materials - Wood (21)	* **DI** - Separate food * **R** - retain heat * **DI** - Economic * **Technological knowledge** - Material properties	Figures 8-10 Figure 14 Figure 18	* **Summarising** three suitable design ideas #3,5,6 * **Proposing** idea #7 * **Proposing** use of plastic * **Elaborating** on the insulator on the inside * **Proposing** idea #8 based on Fig. 18 * **Modifying** idea #8 by having a box inside the bag * **Evaluating** based on context of users - developing an economic intention * **Modify** #8 by using of cardboard and wood as cheap materials and layers to provide strength	* **Makes marks** to indicate suitable and unsuitable ideas, which is summarised * **Looking and pointing** at Figure 14 to propose and justify using separators * **Looking and pointing at Figure 14** to elaborate on using plastic outside and insulation inside * **Looking at Figure 18** to propose, modify and justify #8 * **Gesturing** the use of a box inside a food bag to modify idea #8 * **Looking and pointing to Figure 18** to evaluate the suitability for its context * Looking at P's to modify #8 to be more economic	The event starts off by P1 summarising suitable solutions and asking whether P2&3 has any other solutions. This question then prompts P1 to propose another idea when he looked at Fig.14. During his proposal he identifies that idea #7 has separators. P3 furhter develops his idea. P2 then propose idea #8 by asking if the idea in Fig.18 would not be suitable. P1 continues to modify and justify the design idea proposed by P2. P1 then evaluates idea #8 by asking if the idea wouldnt be too expensive. This question allows P2 to propose the use of cheap wood or cardboard, and justify this idea by saying two layers of material will make the design stronger.

D5 – Micro level analysis

An example of the micro-level analysis is provided in hard copy. The full micro-level analysis can be accessed on the CD-ROM



Episode	Design event	Design move	Part nr	Time	Utterances	Design intentions driving perception-action (Young)	Problem solving goals driving perception-action	External source (1)	Internal Source (1)	Cognitive phase	Cognitive Operation 1	Physical mechanism	Mode of output
Episode 1 *Examining existing ideas*	**1** *Conjuring up ideasby looking at existing products and eliminating based on* ***strength of materials and stability***	1	1	09:47	Kom ons kyk na die idees, die, die, net om 'n idee te kry. Wat gaan in 'n taxi werk ouens? Dit is, dis die main vraag		G - Understanding the problem	Problem statement		1	Reading	Looking at problem statement	Verbal
		2	1	09:50	Hierdie gaan nie, so (trek streep op papier). Nee, ek dink nie so nie.		G - finding suitable solutions	**Figure 6**		2	Adding	Looking at photograph	Writing
		3	2	10:09	Nee...		G - finding suitable solutions	**Figure 7**		2	Adding	Looking at photograph	Verbal
		4	1	10:09	Nee. Hierdie sal dalk?		G - finding suitable solutions	**Figure 8**		2	Adding	Looking at photograph	Writing
		5	3	10:10	Mmm, bietjie harder wees.	DI - strength	G - finding suitable solutions	**Figure 8**		2	Evaluating	Looking at photograph	Verbal
		6	1	10:16	Ok. Die? Ok hierdie gaan reguit afval.	DI - stability	G - finding suitable solutions	**Figure 11**		2	Adding	Looking at photograph	Writing
		7	2	10:25	Uh, hy kan miskien werk as die bokskarton harder is.	DI - strength	G - finding suitable solutions	**Figure 9**		2	Adding	Looking at photograph	Verbal
		8	1	10:30	En hierdie ene? Hierdie sal werk, want hierdie's hard hierdie is cardboard...	DI - strength	G - finding suitable solutions	**Figure 10**		2	Adding	Looking at photograph	Writing

APPENDIX E – EXAMPLES OF VISUAL DATA

E1 – Photographs of original sketches and written notes (CD only)
E2 – Data structuring according to external sources (CD only)

E1 – Photographs of original sketches and written notes

The generated sketches and written notes can be accessed on the CD-ROM

E2 – Data structuring according to external sources

The generated sketches and written notes can be accessed on the CD-ROM

APPENDIX F – POLICY DOCUMENTS

F1 – The Technology CAPS document (CD only)