NOVICE INDUSTRIAL DESIGNERS' HIERARCHICAL THINKING AND IDEA TRANSFORMATION DURING THE PRELIMINARY DESIGN PHASE

by

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Submitted in partial fulfilment of the requirements for the degree

Magister Educationis

in the

Department of Science, Mathematics and Technology Education

Faculty of Education

University of Pretoria

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2019

DECLARATION OF ORIGINALITY

I, **Christiaan Johannes Kamffer**, declare that this dissertation, which I hereby submit for the degree Master Educationis in the Department of Science, Mathematics and Technology Education 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.

Christiaan Johannes Kamffer

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DEGREE AND PROJECT	MEd Novice industrial designers' hierarchical thinking and idea transformation during the preliminary design phase
INVESTIGATOR	Christiaan Kamffer
DEPARTMENT	Science, Mathematics and Technology Education
APPROVAL TO COMMENCE STUDY	21 September 2017
DATE OF CLEARANCE CERTIFICATE	14 March 2019

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ACKNOWLEDGEMENTS

Undertaking this master’s has been a truly life-changing experience for me and it would not have been possible to do without the support and guidance that I received from many people.

Firstly, I thank my supervisors, Dr. Niekie Blom, Mr. Hein Dubery and Dr. Grietjie Haupt (retired), for all the support and encouragement they provided during the long journey in completing this study. Without their guidance and constant feedback this dissertation would not have been achievable.

Secondly, I thank my family and friends for their support and motivation despite my absence in their lives. A special thanks to my parents whose love and guidance are with me in whatever I pursue. They are the ultimate role models. Most importantly, I thank my loving and supportive wife, Dominique, who provides unending inspiration.

Finally, I thank the Lord almighty for His guidance and strength which I experienced every day when faced with difficulties and uncertainties. I acknowledge that You are the one who enabled me to finish my degree. I will keep trusting You and I will keep placing my academic career in Your hands. Thank you, Lord.

ABSTRACT

Design thinking and decision-making during the design process have been found to be hierarchical, representing a general pattern in which designers consider various types of intentions while conceptualising their particular design idea (Haupt, 2018; Vermaas, 2009). Hierarchical thinking can be observed through the investigation of thought development as evidenced in designers' external representation strategies.

The current CAPS document for the subject Engineering Graphics and Design seems to neglect the preliminary design phase of the design process and the connection with hierarchical thinking and idea transformation. As such, research is required to trace novice designers' thinking processes and the transformation of their ideas.

The purpose of this study is to explore and describe how novice designers' hierarchical thinking processes support the transformation of ideas during preliminary design. In order to study the hierarchical thinking and idea transformation of designers, I adopted Extended Design Cognition and hierarchical thinking theories as the conceptual framework in this study. A mixed methods design was employed, embedded in a Critical Realist approach. Four third-year Industrial Design student participants from a local University of Technology in Gauteng were purposefully sampled. Verbal and visual data (sketches, 3D models, physical artefacts and gestures) were generated and documented by means of an in-vivo methodology and analysed qualitatively and quantitatively by means of ATLAS.ti.

This study found that novice designers' consideration of particular abstract aspectual intentions guided the way in which they generated and transformed their ideas. This study also found that they experienced a need to find a fit between their functional intentions and physical elements, allowing them to make both lateral and vertical transformations. This study contributes to the knowledge base on novice designers' design cognition, specifically in terms of designers' hierarchical thinking and idea transformation. To this end, this study provides pedagogical guidelines for current and future EGD teachers.

Key words: Design thinking; Extended Design Cognition Meta-Theory; hierarchical thinking; idea transformation; novice designers; preliminary design phase

LANGUAGE EDITING CERTIFICATE

Exclamation Translations

To whom it may concern

The dissertation entitled, “Novice industrial designers' hierarchical thinking and idea transformation during the preliminary design phase” has been edited and proofread as of 20 June 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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Kind regards

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LIST OF ACRONYMS

2D	Two-dimensional
3D	Three-dimensional
CAPS	Curriculum and Assessment Policy Statement
CAD	Computer Aided Design/Drawing
EGD	Engineering Graphics and Design
FBS	Function-Behaviour-Structure
FET	Further Education and Training
GET	General Education and Training
GMA	General Morphological Analysis
PAT	Practical Assessment Task
PCK	Pedagogical Content Knowledge

CHAPTER 1: ORIENTATION TO THE STUDY

1.1 INTRODUCTION

The purpose of this chapter is to provide insight into the design cognition of Engineering Graphics and Design (EGD) learners and the EGD teacher training in South Africa, as well as industrial designers' design thinking. Subsequently, the problem statement and rationale is discussed, which relates to the seeming lack of practical guidance from the South African Curriculum and Assessment Policy Statement (CAPS) document for EGD to facilitate learners' design cognition. Thereafter, the purpose statement of this study is stated, together with the resulting primary and secondary research questions used to guide the planning and implementation of this study. This is followed by the conceptual framework and research methodology employed in this study. Finally, I conclude this chapter by clarifying the key concepts and presenting the outline and organisation of this dissertation.

1.2 BACKGROUND OF THIS STUDY

Design cognition has been a topic of research for the past half century, and has mainly been defined as the study of the human processing of information during the act of designing (Eastman, 2001). In this regard, design cognition has been characterised as a complex higher-order problem-solving activity (Goel, 1995; Newell & Simon, 1972; Vincenti, 1990), which is due to the ill-structured nature of design problems (Cross, 2011; Goel & Pirolli, 1992; Hay et al., 2017). During such problem-solving activities, designers' understanding of their design problems typically co-evolve with their design solutions throughout the course of the early cognitive phases of the design process (Dorst & Cross, 2001; Goel, 2014; Visser, 2006). Representing their developing understanding and design solutions, designers commonly make physical external representations as a means of communicating their thoughts (Babapour, 2016; Brand, 2018; Stones & Cassidy, 2010). To this end, the typical physical external representations that designers make during the early cognitive phases are quick and roughly drawn sketches, as well as quickly made, low-resolution physical models (Brand, 2018).

Several scholars have acknowledged the importance of developing learners' design cognition in Technology Education (De Vries et al., 2016; Haupt, 2017; Kelley & Knowles, 2016). Technology Education provides students the opportunity to learn topics covering technological processes, such as designing, making, problem solving, and technological systems while engaging in ill-structured problem solving (Gumbo, 2016; Hay et al., 2017). Over the past few decades, Technology Education as a field of study has come to include a focus on engineering, resulting in a variety of new curricula that have emerged worldwide (Kelley, 2008), such as EGD. In the South African context, EGD is an elective Further Education and Training (FET) subject from Grades 10 to 12, along with Civil, Mechanical and Electrical Technology (DoBE, 2011a; Makgato, 2003; Stevens, 2006). These subjects are taken after technology as a General Education and Training (GET) subject from Grades 7 to 9 (DoBE, 2011b; Makgato, 2003; Stevens, 2006). However, it has been noted that there are currently limited frameworks to characterise how learners in FET subjects engage in thinking, and the use of conceptual and procedural knowledge during practical work (Stevens, 2006). For this study, I therefore aimed to develop a conceptual framework in this emerging field by investigating how novice industrial designers think during the early cognitive phases of the design process.

1.2.1 South African Engineering Graphics and Design Curriculum

The way in which learners engage in design thinking should be seen in terms of the South African CAPS document for EGD (see Appendix F1). The purpose of EGD is to teach learners internationally acknowledged drawing principles for both academic and practical application (DoBE, 2011a, p. 8). The CAPS document further emphasises six specific aims (DoBE, 2011a, pp. 8-9) in which learners have to:

- View drawings as the primary means of communication in the technological world;
- Gain specific basic knowledge within the contexts of Mechanical, Civil and Electrical Technology;
- Gain various instrument and freehand drawing techniques;

- Solve technical problems by means of drawings;
- Apply the design process; and
- Learn to use Computer Aided Design/Drawing (CAD).

In order to address these aims, learners are given a Practical Assessment Task (PAT), which is considered as the practical examination that counts 25% towards learners' final marks at the end of the year (DoBE, 2019). The purpose of the PAT is to introduce learners to the design process with a socio-technical problem and provide them with the opportunity to integrate and apply their acquired drawing knowledge and techniques to the design process (DoBE, 2019, pp. 3-4). Learners are only allowed to engage with the PAT during the allocated time at the end of the first three terms under the supervision of an EGD teacher. During their engagement, teachers instruct the learners on how they should go about the design process. The EGD design process typically focuses on the parts relevant to drawing (van Leeuwen & du Plooy, 2015, p. 128), which include (DoBE, 2011a, p. 16):

- Problem identification;
- Formulating a design brief and list specifications and/or constraints;
- Conducting research and generating graphical ideas/concepts;
- Selecting the most suitable solution within the context of the design brief;
- Presenting the final solution as working and 3D drawings; and
- Evaluating of the entire process.

However, during my investigation of the PAT (see Appendix F2), I found that the PAT predominantly expects learners to produce comprehensive, detailed sketches and working drawings. This means that learners are expected to generate ideas analytically through detailed free-hand sketches and then produce working drawings from these sketches (DoBE, 2019). Looking at both the PAT and CAPS document, there is no guidance or instruction on how teachers should facilitate learners' generation of ideas. Furthermore, far too little attention is paid to the use of quick and roughly made sketches and physical models, and how learners generate and incrementally transform their ideas into solution outputs through sketch making and physical modelling. This therefore suggests that the EGD curriculum neglects the design process and its cognitive connection with the physical external representation of ideas. This seems problematic since it is expected from learners to use sketching techniques only to represent various possible design solutions (DoBE, 2019, p. 4). Yet, insufficient time and guidance are provided to foster learners' design thinking.

1.2.2 South African Engineering Graphics and Design teacher training

Individuals aspiring to become an EGD teacher can enrol for a four-year Bachelor of Education degree at various universities in South Africa. The EGD curriculum at South African universities, according to Khoza (2017), are specially designed to equip pre-service teachers to be able to teach EGD at secondary schools and FET colleges upon completion of their degree. During the course of the degree, pre-service teachers in their fourth year of study have the opportunity visit a number of schools for their teaching practice. During their teaching practice, which is over a period of up to sixteen weeks a year depending on the requirements of each university, they would typically observe how their mentor teachers present lessons and then themselves present lessons for critique.

Over the past decade, various studies have been conducted on pre- and in-service EGD teachers. Several studies have identified that pre-service teachers lack the necessary spatial visualisation skills to be able to teach (Khoza, 2014; Makgato & Khoza, 2016a, 2016b), which according to Nagy-Kondor (2017) is a pre-requisite for successfully teaching technical education. In an instructional intervention study conducted over a 20-year period, Potter and van der Merwe (2003) found that students with under-developed spatial visualisation skills are at a disadvantage with respect to studying EGD, and stressed that early identification is important. Furthermore, their study reports that African students have among the most under-developed spatial visualisation skills, which is due to the increasingly diverse enrolment of students at South African universities from disadvantaged educational backgrounds (Potter & van der Merwe, 2003). However, they developed an instructional model for developing students' spatial visualisation skills, involving students having to sketch and physically model how they perceive given three-dimensional (3D) objects (Potter & van der Merwe, 2003). An instructional model like this is also supported by Kok and Bayaga (2019).

Furthermore, several other studies have identified that in-service teachers lack the necessary Pedagogical Content Knowledge (PCK) for teaching EGD, especially the topics regarding assembly drawings (Singh-Pillay & Sotsaka, 2017; Sotsaka, 2015) and sectional drawings (Khoza, 2013; Makgato & Khoza, 2016a). In order to fill this gap, Singh-Pillay and Sotsaka (2017) suggest that in-service EGD teachers should undergo continuous professional development and attend workshops during curriculum reformation. In addition, Khoza (2013) has proposed a model of teaching and learning, specifically for the topic, regarding sectional drawings, which I believe could be applied to most topics in EGD.

However, previous research did not take into consideration the pre- and in-service EGD teachers' ability to facilitate design cognition, such as hierarchical thinking and idea transformation. The research also did not consider the seeming lack of guidance that exists for EGD teachers' to facilitate learners' design cognition. In this regard, I conducted this study with the aim of providing practical guidelines for facilitating pre- and in-service EGD teachers.

1.2.3 Industrial designers' design thinking

In South African tertiary education, there have been concerns that Technology Education at secondary school level does not place enough emphasis on designing (Smit, 2010). A further concern, according to Smit (2010), is that first-year students generally lack an understanding of design in various design-related fields of study, especially in the field of Industrial Design. In this regard, I therefore focused on the design thinking of novice design students in the Industrial Design field of study. According to Tovey (1989), industrial designers are trained to think broadly and deeply, addressing design problems with manufactured products, specifically the parts that come into contact with humans. The design problems that industrial designers engage with typically involve a large number of constraints to meet goals that are not clearly stated (Green & Bonollo, 2003). This implies that these design problems are generally of an ill-structured nature. The reason for focusing on industrial designers, specifically novice Industrial Design students, is that the design problems that they typically engage with are similar to the design problems that EGD learners are expected to solve in the annual PAT (see Appendix F2). These design problems typically expect both students and learners to improve the functional and/or physical design of parts of an existing artefact.

Furthermore, according to Hegeman (2008), design cognition has not yet been fully understood, and designers themselves struggle to explain how they generate and transform design ideas. However, design educators should provide support to their students to understand their own design processes and, through metacognition, develop their own ways of bringing design thinking and action to problem solving (Stables, 2014). One way of investigating how designers think during problem-solving activities is through the lens of hierarchical thinking.

The notion of hierarchical thinking, as explained by Allen and Starr (2018), originates from the Hierarchy Theory, a division of the General Systems Theory that is concerned with how humans address a complex system, and consists of a set of levels organised according to a rank. A hierarchical system of thinking indicates that there exists a relationship between the starting level and the following levels (Medland, 2007). This, in terms of design cognition, implies that designers first think of 'something' regarding a particular context, which is followed by subsequent thoughts of 'something else' regarding other contexts. Examples of designers' hierarchical thinking can be seen in the situated Function-Behaviour-Structure (FBS) framework developed by (Gero, 1998); the model of the conceptual layering of technical devices proposed by Vermaas (2009), which is built on the model of technical devices developed by Brown and Blessing (2005); and the cognitive tool for guiding coherent decision making developed by Haupt (2018). All of these models of hierarchical thinking look at how designers think regarding the functionality, behaviour and physicality of the artefact that they are designing, and how these thoughts link with one another during preliminary design.

1.3 PROBLEM STATEMENT AND RATIONALE

The research problem of this study was derived from the preliminary reading of the literature on Extended Design Cognition, the current EGD curriculum in South Africa, and challenges regarding EGD teacher training and industrial designers' design thinking. The literature regarding the design cognition of novice designers, in particular, does not sufficiently explain how their thoughts develop in a hierarchical manner, and how they link their abstract thoughts with how they generate and transform design ideas (Goel, 1995; Haupt, 2018).

As far as the design cognition involves designers thinking hierarchically, much more focus has been placed on expert designers' hierarchical thinking than on that of novice designers (Cross, 2011; Haupt, 2018; Vermaas & Dorst, 2007). Some studies have already found that expert problem solving in any design domain involves hierarchical structures (Blount & Clarke, 1994). This finding is supported by Haupt (2018), who investigated expert designers' design cognition in the fields of Architecture, Mechanical Engineering and Industrial Design. She found that the way in which the expert designers think about their design solutions could be typified in a hierarchical structure (Haupt, 2015). Based on the findings of this study, I attempted to develop a hierarchical structure that represents the design cognition behaviour of novice Industrial designers. Thus, if design educators utilise the hierarchical structure in their teachings, they could educate novice designers to become aware of their intentional thoughts. Consequently, if EGD learners are educated to be attentive to the various levels of intentions of their hierarchical thoughts, tertiary education related to various fields of design could produce designers that perform a higher degree of idea transformations.

In the context of South Africa, limited research has previously been conducted on EGD teachers that focuses on their lack of PCK teaching skills (Khoza, 2013; Makgato & Khoza, 2016a; Singh-Pillay & Sotsaka, 2017; Sotsaka, 2015) and spatial visualisation skills (Khoza, 2014; Makgato & Khoza, 2016a, 2016b). However, none of the previous studies focused on how EGD teachers should facilitate the design cognition of EGD learners. The current CAPS document for EGD (DoBE, 2011a) states that teaching should promote active learning in which learners develop practical solutions to identified problems in a given real-world context (DoBE, 2011a, pp. 4-5). However, neither the CAPS nor the PAT documents (DoBE, 2011a, 2019) provide guidelines to help teachers to foster learners' design thinking. More specifically, appropriate strategies for fostering learners' abstract ideas into concrete solutions in a hierarchical manner are not specified. If the EGD curriculum fails to provide effective and appropriate guidelines for the facilitation of learners' design thinking, then teachers might not be able to foster learners' hierarchical thinking, which lies at the foundation of the generation and transformation of design ideas.

To this end, I decided to investigate the way in which novice design students in the field of Industrial Design think by using an Extended Design Cognition lens (Blom, Haupt, & Fraser, 2018; Haupt, 2018), since their design problems are similar to those that EGD learners are expected to solve. The benefit of following such an integrated theoretical approach is its descriptive power in describing the development of designers' moment-to-moment design cognition. Its value is specifically in describing how novice Industrial Design students' hierarchical thoughts develop while they are generating and transforming ideas through making physical external representations. By establishing how novice Industrial Design students' intentional thoughts develop hierarchically while generating and transforming ideas, I derived practical guidelines for EGD teachers. Deriving practical guidelines might help EGD teachers to draw their learners' attention to the various levels of intentions in hierarchical thinking. In turn, this might assist the learners to contextualise their thoughts, enabling them to generate design ideas and make lateral and vertical transformations.

1.4 PURPOSE STATEMENT

In the light of the problem statement and rationale, the purpose of this study was to explore and describe how novice Industrial Design students' hierarchical thinking supports the development of their idea transformations during the preliminary design phase. The focus was on how novice designers considered the various hierarchical levels of intentions and how these intentions guided and supported the way in which they generated initial ideas and the transformation thereof.

1.5 RESEARCH QUESTIONS

In accordance with the purpose statement and rationale, I formulated the primary research question that guided the planning and implementation of this study:

How does novice industrial designers' hierarchical thinking support the development of their idea transformations during the preliminary design phase?

In order to address the primary research question and limit the scope, I formulated the following secondary research questions:

1. How do novice industrial designers’ aspectual intentions support their idea transformations during the preliminary design phase?
2. How do novice industrial designers’ functional intentions support their idea transformations during the preliminary design phase?
3. How do novice industrial designers’ physical elements support their idea transformations during the preliminary design phase?
4. How do novice industrial designers’ implementation intentions support their idea transformations during the preliminary design phase?

1.6 CONCEPTUAL FRAMEWORK OF THIS STUDY

For this study, I adapted Haupt’s (2018) Model of Hierarchical Thinking as my conceptual framework. The conceptual framework is informed by theoretical underpinnings from the Extended Design Cognition Theory, which is concerned with how designers’ minds extend into the physical environment allowing them access to both internal and external information sources. The suitability of this conceptual framework is based on its focus on describing novice industrial designers’ hierarchical thinking processes and how their levels of intentions supported their idea transformations while making physical external representations. The conceptual framework for this study is illustrated in Figure 1.1.

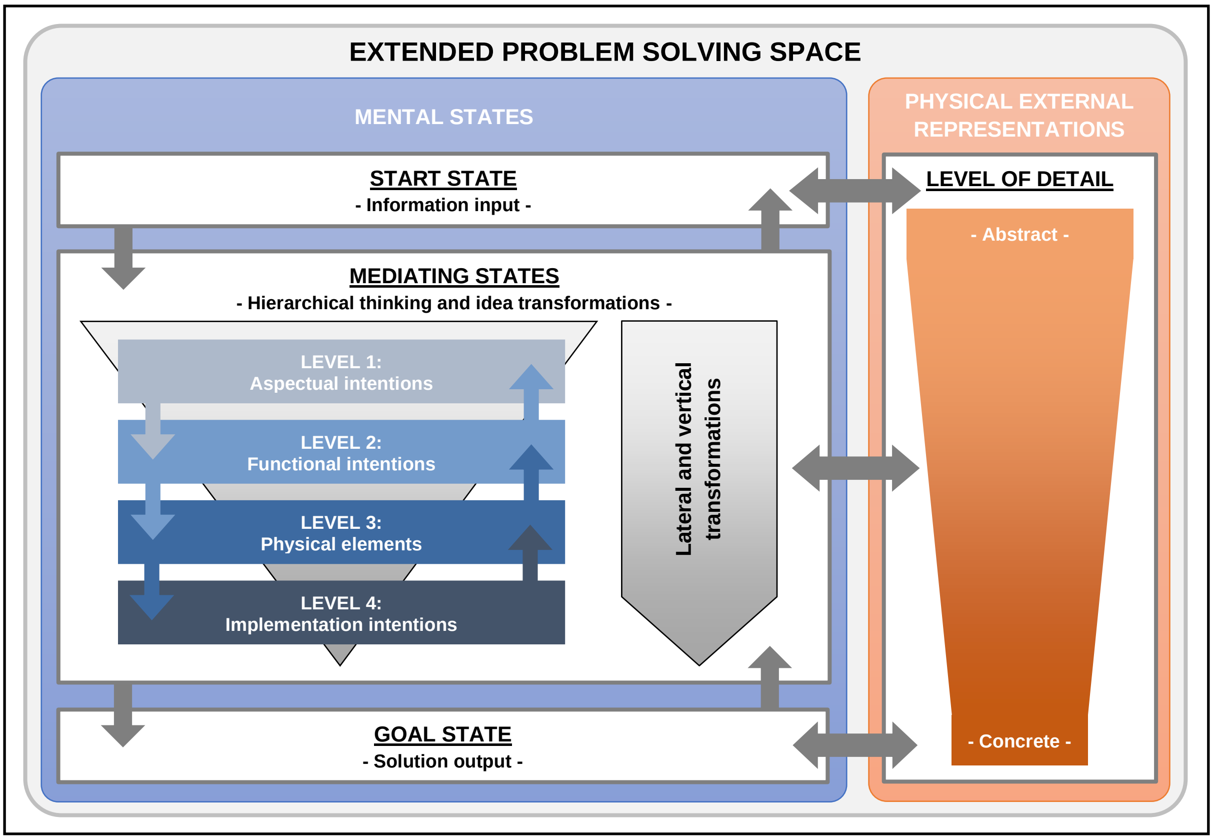


Figure 1.1: Conceptual framework of this study

Figure 1.1 illustrates the conceptual framework of this study, which was adapted from the Hierarchical Thinking Model from Haupt (2018). The conceptual framework includes designers' mental states and the physical external representations they make, working in a top-down manner. Designers' mental states consist of three states, namely, the start, mediating and goal states. For this study, I specifically focused on the mediating states where both designers' hierarchical thinking and idea transformations were evident. Designers' hierarchical thinking in the mediating state starts with aspectual intentions (level 1) and is subsequently followed by functional intentions (level 2), physical elements (level 3), and implementation intentions (level 4). During designers' hierarchical thinking, they generate and transform ideas, which are assumed to be supported by their various levels of intentions. Designers' transformation of their design ideas would typically include lateral and vertical transformations (Goel, 1995).

With regard to physical external representations, designers would typically externalise their thoughts by making physical external representations, such as sketches and physical models. Their physical external representations range from being abstract to concrete representations of thought (Babapour, 2016; Visser, 2006). The conceptual framework is discussed in detail in Section 2.6.

1.7 SIGNIFICANCE OF THE STUDY

During the planning of this study, I noticed shortcomings in facilitating the design thinking of novice designers during the preliminary design phase, especially in a South African EGD context. This study might therefore draw the attention of educators, curriculum developers and other researchers to the seemingly limited research and lack of guidance for facilitating learners' design cognition in the South African context. This study provided an opportunity to make theoretical and professional practice contributions.

With regard to theory, the findings presented in this study might add to the existing literature on novice design cognition in general. Moreover, I hope to further develop the Hierarchical Thinking Model of Haupt (2018) in an educational setting. By describing how novice industrial designers' hierarchical thinking supports their idea transformations, I hope to provide a framework for future investigations on the design cognition of novice designers within the EGD context.

In terms of professional practice, I aimed to provide guidelines based on how novice industrial designers' hierarchical thinking supported their idea transformations. These guidelines could potentially be included in EGD teacher training courses and teacher development programmes to educate pre- and in-service teachers on the role that hierarchical thinking plays in supporting learners' idea transformations. This could deliver teachers who would be able to facilitate novice design cognition.

1.8 RESEARCH METHODOLOGY

I adopted a critical realist stance for this study in order to study the observable and unobservable structures, mechanisms and interactions of novice designers with their internal and physical environments in order to explain the occurrence of a given set of events (Bhaskar, 1975; Danermark, Ekstrom, Jakobsen, Karlsson, & Bhaskar, 2002; Wynn & Williams, 2012). Extended Design Cognition, as the meta-theory of this study, allowed me to study novice designers' internal and external processing of information in order to provide in-depth explanations of their hierarchical thinking whilst transforming their design ideas. Furthermore, a critical realist viewpoint enabled me to focus on how novice industrial designers' various hierarchical thinking levels developed as they interacted with internal and external information, and how their hierarchical thoughts supported their lateral and vertical transformation of design ideas. I was also able to capture various types of data evidencing hierarchical thinking and idea transformation processes (Wynn & Williams, 2012). In this way, I was able to address my research questions to describe how the participants' hierarchical thinking supported their idea transformations. I further elaborate on my paradigmatic assumptions in Section 3.2.

Based on this study's paradigmatic assumptions, I followed a concurrent mixed methods research approach (Maree, 2016; Tashakkori & Teddlie, 2010). This allowed me to capture both qualitative and quantitative data wherein qualitative data took dominance (QUAL+quan) (Creswell, 2014). The qualitative data consisted of concurrent verbal and visual data types, whereas the quantitative data consisted of temporal data. Capturing multiple data types seemed necessary to provide rich descriptions of the participants' design cognition (Creswell, 2014). The research approach I followed for this study is further explained in Section 3.3.

In this study, I adopted a descriptive case study research design (Stake, 2018; Yin, 2014; Yin & Campbell, 2018), allowing me to study novice Industrial Design students' hierarchical thinking processes. The research site for this case study was situated in the Industrial Design studio of a local University of Technology in Gauteng, where the participants of this study normally went about their design activities. This allowed me to observe the participants' naturalistic design behaviour where they felt the most comfortable engaging with a design task (Carroll & Johnson, 1990).

The local University of Technology in Gauteng, where the research site was situated, was conveniently selected (Daniel, 2012; Teddlie & Yu, 2007) and based on their fully operational Industrial Design studio. The sample of this study was purposefully selected (Daniel, 2012; Teddlie & Yu, 2007) and was comprised of four top-achieving third-year Industrial Design students from the Faculty of Engineering. The participants were selected with the input of their responsible lecturer, according to a set of selection criteria from which much could be learned from the participants. The sample selection process is further elaborated on in Section 3.5.

For this study, I adopted an in-vivo methodology as the data generation setup (Dunbar, 2000, 2001). This allowed me to investigate the participants' naturalistic cognitive processes and natural dialogue (Ormerod & Ball, 2017) while they were engaged with a problem in their normal environment situated in the Industrial Design studio. Ensuring the participants natural workflow, I considered this study as a case in which I took a non-participatory observer stance. Conducting this study in this manner enhanced objectivity, which also falls in line with the critical realist paradigm employed in this study (Cohen, Manion, & Morrison, 2018).

In order to elicit each team of participants' design cognition behaviour, the lecturer responsible for the third-year Industrial Design student cohort crafted the design task for the participants, which was used as the data generation instrument for this study. The participants were required to design a *hand-held or counter-top hand operative machine that is a cost-effective alternative to making Nespresso coffee pods*. They only had five hours to work on the given instructions of the design task. The design task played an important role in eliciting the participants' cognitive behaviour, more specifically, their hierarchical thinking and idea transformation processes. The data generation strategy is further explained in Section 3.6.

I furthermore structured, analysed and interpreted the concurrent data by applying a multi-level analysis procedure derived from Ash (2007). This allowed me to reduce the captured data into manageable amounts without the loss of complexity (Haupt, 2013; Tashakkori & Teddlie, 2010). Additionally, this also allowed me to identify emerging connections or patterns (Goel & Pirolli, 1992; Haupt, 2013) from the *a-priori* theoretical constructs embedded in the conceptual framework. The data analysis and interpretation procedure are further explained in Section 3.7.

In order to ensure that the research conducted in this study was authentic, I carried out quality assurance measures. This study utilised an in-vivo methodology, which implied the integration of qualitative and quantitative quality assurance measures to generate trustworthy, valid and reliable findings. I addressed the research in a naturalistic manner by placing emphasis on honesty, depth and richness of the data generated by the participants (Cohen et al., 2018; Shenton, 2004). For the qualitative part of this study, I adhered to four trustworthiness measures (Lincoln & Guba, 1985), namely, credibility, transferability, confirmability and dependability. For the quantitative part of this study, I adhered to five measures of validity and reliability, namely, construct validity, internal validity, face validity, content validity, and inter-rater reliability. The trustworthiness, validity and reliability measures are further elaborated on in Section 3.8.

In order to ensure that this research was conducted in an ethical manner, I acquired permission from various authorities. Permission was granted from the Ethics Committee of the University of Pretoria's Faculty of Education, the Ethics Committee of a local University of Technology in Gauteng's Faculty of Engineering and Built Environment, the Head of the Department of Industrial Design studies, and the responsible lecturer for the participants. Thereafter, I gave letters of informed consent to the students, informing them about the purpose and procedures of this study, as well as their rights as participants and the ethical principles followed (Cohen et al., 2018; Maree, 2016). These principles included voluntary participation, safety during participation, privacy, trust, and reciprocal benefits. The ethical principles are further discussed in Section 3.9.

1.9 CLARIFYING KEY CONCEPTS

In this section, I explain the key concepts underlying the theoretical assumptions of this dissertation in order to demonstrate an appreciation of the purpose, focus, and potential contributions of this study.

1.9.1 Early cognitive phases of the design process

The early cognitive phases of a design process are initial cognitive phases that designers exhibit during their design processes. The distinct cognitive phases inherent in the design problem-solving space (Goel, 1995) are the problem structuring and problem-solving phases. Designers typically engage in problem structuring in order to find and make sense of missing information about the problem that was not provided by the design brief (Goel, 1995). Designers typically engage in problem solving in order to generate and explore solutions that have emerged from the problem structuring phase (Goel, 1995).

1.9.2 Extended cognition

The Theory of Extended Cognition is based on the integration of the classic Information Processing Theory from Newell and Simon (1972) and Embodiment theories. Extended cognition recognises that designers not only process information within the mind, but also extend their cognitive processes beyond their mind (Clark & Chalmers, 2010). Designers extending their minds into the physical environment allow them to access and utilise internal and external information sources. These information sources are typically processed internally and externally and physically externalised through sketches and physical models (Goel & Pirolli, 1992; Suwa, Purcell, & Gero, 1998).

1.9.3 Physical external representations

Physical external representations are designers' externalised thoughts about internally and externally processed information and typically take the shape of sketches, physical models or artefacts (Hay et al., 2017; Visser, 2006). Designers' physical external representations range from vague and abstract representations to detailed and concrete representations of ideas. The level of detail is dependent on designers' level of certainty and commitment to particular ideas and the cognitive phase in which they find themselves (Goel, 1995; Haupt, 2013).

1.9.4 Hierarchical thinking

The notion of hierarchical thinking, as explained by Allen and Starr (2018), originates from the Hierarchy Theory, a division of the General Systems Theory, which is concerned with how humans address a complex system. Hierarchical thinking consists of a set of levels organised according to rank (Allen & Starr, 2018). Hierarchical thinking, in the context of this study, can therefore be understood as seeing novice designers' design cognition organised in levels that are commensurate with design learning (Oxman, 2001).

1.9.5 Idea transformation

The transformation of ideas refers to a cognitive thinking strategy regarding how an idea develops over time (Prats & Earl, 2006; Rodgers, Green, & Mcgown, 2000). Goel (1995) identified two types of transformations associated with the development of ideas, namely, lateral and vertical transformation. Lateral transformation occurs when designers transform from one idea to a slightly different alternative idea, whereas vertical transformation occurs when designers transform from one idea to a more detailed version of that same idea (Goel, 1995).

1.9.6 Industrial design

Industrial Design is an industry concerned with the design of manufactured products, specifically, the parts that come into contact with humans (Tovey, 1989), and the integration of ergonomics, construction, engineering and the aesthetics of designing these items (Dorst & Cross, 2001). This involves industrial designers engaging in creating and developing designs and specifications that enhance the use, function, value, and appearance of everyday functional items (Vanchan, 2007), such as kettles, furniture, electronic devices, amongst others.

1.9.7 Novice designers

The expertise of novice designers, as defined by Dorst and Reymen (2004), is when designers consider objective features of a situation by following strict rules provided by experts in order to deal with the problem. The expertise of novices are still evolving. This means that novices generally do not have enough information to recall from past design experiences to solve given design tasks (Cross, 2004). Novices typically decompose given design problems by sequentially recognising and exploring the sub-solutions of the problem with trial-and-error techniques (Dreyfus & Dreyfus, 1980).

1.9.8 Preliminary design phase

During the preliminary design phase, designers typically generate and explore ideas that could possibly address the given ill-structured problem (Goel, 1995). These ideas emerge from designers' incremental transformations, and are low in detail and not fully developed (Goel & Pirolli, 1992).

1.10 OUTLINE AND ORGANISATION OF THIS STUDY

This dissertation consists of five chapters, which comprise the following:

Chapter 1: Orientation to this study

Chapter 1 provides an overview of this study where I specifically referred to the background, problem statement, rationale and purpose statement that I addressed in this study. I briefly discussed the conceptual framework used, which guided my theoretical and methodological decisions. Thereafter, I briefly reviewed my methodological decisions, as well as clarifying the key terms in the study.

Chapter 2: Literature review

Chapter 2 provides an overview of the developing field of cognition in Industrial Design. I also discuss the theoretical underpinnings of this study where I specifically refer to the Extended Design Cognition Theory that is typically used to describe the cognition of designers. Thereafter, I discuss the early cognitive phases of the design process, as well as the roles that physical external representations play in designers' cognition. I conclude the chapter by discussing the conceptual framework utilised to study the design cognition of novice designers.

Chapter 3: Research methodology

Chapter 3 provides the methodology that I designed to generate data that could address my research questions. I discuss, *inter alia*, the paradigmatic assumptions on which I based this study, which necessitated a qualitative dominant concurrent mixed methods research approach. Furthermore, I explain and justify the research design, sampling methods and criteria, data generation strategies and data analysis, and interpretation of this study. Finally, I discuss the quality assurance measures that I adhered to, as well as explaining the ethical considerations that I took into account in implementing this study.

Chapter 4: Results and findings of this study

Chapter 4 presents the results and findings of this study and explains how I interpreted the generated data in order to answer the research questions. In terms of my interpretation of the hierarchical thinking of the participants, I reveal the number of occurrences of each level of intentions and emphasise how these intentions linked with one another. Thereafter, in terms of my interpretation of the idea transformation process of the participants, I reveal each team of participants' idea transformation structure and show how the levels of intentions shaped their idea transformation structure.

Chapter 5: Conclusion, limitations and recommendations

Chapter 5 presents a summary of the key findings of this study and the conclusions that I was able to draw in relation to the formulated research questions. In stating the conclusions of this study, I list the potential contributions this study might make in terms of theory and professional practice. I conclude this chapter by reporting some limitations that occurred during this study, as well as presenting recommendations for professional practice and future research.

1.11 CONCLUSION

In this chapter, I presented the background of the current challenges faced in using the EGD curriculum, particularly how novice design cognition is currently facilitated. Furthermore, I explained the research problem, which is based on the seeming lack of guidelines in the EGD CAPS document with regard to how learners might hierarchically structure their thoughts to support their idea transformations during the preliminary design phase. This was followed by the rationale, which is focused on how hierarchical thinking models that explain the design cognition of EGD learners might provide theoretical and professional practice contributions. Thereafter, I stated the research questions that guided the planning and implementation of this study, followed by an explanation of the conceptual framework and research methodology I employed in this study. The potential contributions of this study were also discussed in terms of theory and professional practice. I concluded this chapter by clarifying key concepts and presenting the outline and organisation of this dissertation. In Chapter 2, I discuss literature regarding the design cognition in the field of Industrial Design, which is followed by literature regarding Extended Design Cognition and the role physical external representations play in novice designers' design cognition. Thereafter, I discuss the conceptual framework used for this study.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

The purpose of this chapter is to gain an understanding of novice designers' hierarchical thoughts during the early cognitive phases of the design process. The literature on design cognition shows copious research conducted on expert designers in relation to the modicum of research on the design cognition of novice designers (Cross, 2004; Eastman, 2001; Lawson, 2006). Much of the literature to date tends to focus on design cognition classifying *what* designers think, yet in the current literature uncertainties still exist regarding classifying *how* designers think (Cross, 2011).

In this chapter, I review the literature underlying the conceptual framework utilised to address the research questions posed in this study (Chapter 1, Section 1.7). I start this chapter by firstly providing an overview of design cognition in the field of Industrial Design, and describe the current literature on hierarchical thinking and idea transformation during the preliminary design phase. Secondly, I outline an Extended Design Cognition approach as the meta-theory for studying how novice designers think during the early cognitive phases of the design process. Thirdly, I discuss previous studies focusing on the role that physical external representations play in novice designers' design cognition. Lastly, I discuss the conceptual framework of this study, which is based on Haupt's (2018) Model of Hierarchical Thinking.

2.2 OVERVIEW OF DESIGN COGNITION IN THE FIELD OF INDUSTRIAL DESIGN

Design cognition has been the topic of research for many decades, where researchers have reflected and debated on fundamental and philosophical approaches to generic design (Goel, 2014; Love, 2002; Visser, 2006). The growing understanding of design led to the belief that designing is a cognitive behaviour that involves problem-solving activities (Lawson, 2006; Visser, 2006). During such problem-solving activities, many scholars (Dorst & Cross, 2001; Goel, 2014; Visser, 2006) found that designers' understanding of their design problems typically co-evolves with their design solutions throughout the course of the design process. This means that industrial designers' process of designing is characterised by iteratively understanding the design problem and defining appropriate design specifications, while they are searching for and evaluating design solutions (Green & Bonollo, 2003; Maher & de Silva Garza, 2006). In this regard, this study focuses on the way in which industrial designers co-evolve their design solutions during preliminary problem solving.

Previous studies have also highlighted that expert industrial designers' problem-solving activities are generally solution- and knowledge-focused (Kruger & Cross, 2006; Lu, 2015). This means that experts utilise their prior, structured and personal knowledge to generate solutions, and spend less time on gathering information to understand the design problem. In contrast, novice industrial designers are generally problem-focused (Vasconcelos, Crilly, Chen, Campos, & Kelner, 2016), and experience the need to gather information typically not present at the start of a project (Haug, 2015; Laing & Masoodian, 2016). However, experts and novices alike produce a great variety of designs that are not necessarily influenced by their prior design ideas (Goldschmidt & Smolkov, 2006; Purcell & Gero, 1991). Literature exists on the ways in which industrial designers engage with problem solving. What remains unclear, however, is how industrial designers' thoughts direct them in generating such a large amount of design ideas, as well as how they transform these ideas to become solutions. It is within this literature gap that this study finds its implication. For this study, I looked at how novice industrial designers thoughts are organised, as well as how these organised thoughts direct the way in which they generate and transform their design ideas during preliminary problem solving. In this regard, this study looked at how designers think hierarchically, as well as how they transform their ideas. In the following sections, I discuss the definition of hierarchical thinking and idea transformations, as well as current models in terms of design cognition and their implication for this study.

2.2.1 Hierarchical thinking

The notion of hierarchical thinking, as explained by Allen and Starr (2018), originates from the Hierarchy Theory, a division of the General Systems Theory, which is concerned with describing human behaviour when addressing complex problems (Merali & Allen, 2011). A hierarchical system consists of a set of levels, and is organised according to rank ranging from low to high (Allen & Starr, 2018; Wu, 2013), in which there exists relationships between the lowest levels and the following higher levels (Medland, 2007). Allen (2009) states that lower levels operate quicker and at a higher frequency than higher levels, and that higher levels exert constraints on lower levels. However, according to Wu (2013), Hierarchy Theory acknowledges both bottom-up processes, relationships from the lowest to the highest level; and top-down influences, relationships from the highest to the lowest level. A proper balance between bottom-up and top-down approaches in a hierarchical system is key to the performance and persistence in addressing complex problems (Wu, 2013).

With regard to hierarchical thinking in terms of design cognition, several models have been developed to investigate designers' thought processes when engaged with a design problem. Some of these models are the situated Function-Behaviour-Structure (FBS) framework developed by Gero (1998), and the Model of Conceptual Layering of Technical Devices proposed by Vermaas (2009), which is built on the Model of Technical Devices developed by Brown and Blessing (2005).

In the situated FBS framework, Gero (1998) placed emphasis on three levels of variables describing different aspects of an artefact, namely, function, behaviour and structure. The framework indicates that designers make links between function, behaviour and structure. Specifically, it shows how designers link function to behaviour and how they derive behaviour from structure, although no direct link exists between function and structure (Gero & Kannengiesser, 2004). Furthermore, Gero (1998) claimed that there are eight fundamental processes involved in designing, namely (Gero & Kannengiesser, 2004, pp. 374-375):

> Formulation (transforming the design requirements, expressed in function, into behaviour that is expected to enable this function), synthesis (transforming the expected behaviour into a solution structure that is intended to exhibit this desired behaviour), analysis (deriving the 'actual' behaviour from the synthesised structure), evaluation (comparing the behaviour derived from structure with the expected behaviour to prepare the decision if the design solution is to be accepted), documentation (producing design descriptions for constructing the artefact), reformulation type 1 (addressing changes in terms of structure variables or ranges of values for them if the actual behaviour is evaluated to be unsatisfactory), reformulation type 2: (addressing changes in terms of behaviour variables or ranges of values for them if the actual behaviour is evaluated to be unsatisfactory), and reformulation

type 3: (addressing changes in terms of function variables or ranges of values for them if the actual behaviour is evaluated to be unsatisfactory).

The limitation of this framework is that the definitions describing this framework are unstable in allowing the double status of describing and prescribing designers' problem-solving activities (Vermaas & Dorst, 2007).

In the Model of Conceptual Layering of Technical Devices, Vermaas (2009), built on the Model of Technical Devices, first developed by Brown and Blessing (2005). The Model of Technical Devices originally consisted of four levels, namely, goal, action, function and behaviour (Brown & Blessing, 2005). However, a fifth level, structure, was emphasised (Vermaas, 2009). In this model, Vermaas (2009) states that the first three levels (goal, action and function) consist of descriptions containing designers' intentions, whereas the remaining levels (behaviour and structure) consist of descriptions explaining the physico-chemical state in which an artefact is used and when it is not used. Furthermore, this model adopts both bottom-up and top-down approaches (Vermaas, 2009). The bottom-up approach, called agentive perspective, focuses on a designer's subjective intention to define what is required from an artefact given a specific goal, whereas the top-down approach, called structural perspective, focuses on a designer's objective intention to define the structure of an artefact (Vermaas, 2009). The limitation of this model is that it focuses on describing experts' solution-focused problem-solving behaviour, whereas this study focuses on novice designers' problem-focused approach to problem solving. Both these models of hierarchical thinking look at how designers think with regard to the functionality, behaviour and physicality of the artefact they are designing, as well as how these thoughts link with one another. However, these models of hierarchical thinking did not look at designers' intention to implement their thoughts about functionality, behaviour and physicality.

In this study, I not only looked at how novice industrial designers' thoughts about functionality, behaviour and physicality link with one another, but also how they selected and implemented these thoughts. I therefore decided to utilise the Hierarchical Thinking Model developed by Haupt (2018), which are further discussed in Section 2.6. In this regard, I was able to trace novice industrial designers' thoughts in order to investigate the transformation of their ideas.

2.2.2 Idea transformation

The notion of idea transformations refers to how designers move from one design idea to the next. Goldschmidt (1995, p. 195) explains that a ‘move’ is “a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move”. For this study, a ‘move’ is regarded as designers’ intention to transform their design ideas towards a solution (Huang, 2008). Goel (1995), who conducted one of the most detailed studies in design cognition, developed the typology of transformation through discovering and defining the act of sketching (Chen, You, & Lee, 2003; Prats & Earl, 2006; Rodgers et al., 2000). The typology comprises two operations for transforming ideas, namely, lateral transformations and vertical transformations (Goel, 1995, 2014). Lateral transformation facilitates the broadening of the problem space (Goel, 2014), and typically takes place during preliminary problem solving (Goel, 1995; Haupt, 2018). During lateral transformations, designers move from one idea to a slightly different alternative idea (Goel, 1995). This indicates that designers are still uncertain and therefore lack commitment to their design ideas (Goel, 2014). Vertical transformation facilitates the deepening of the problem space (Goel, 2014), and typically takes place during detail problem solving (Goel, 1995; Haupt, 2018). During vertical transformations, designers move from one idea to a more detailed version of the same idea (Goel, 1995). This indicates that designers start to become more certain and therefore become committed to their design ideas, attempting to add more detail over time (Goel, 2014).

Previous studies investigating how designers’ ideas transform through sketch-making (Cai, Do, & Zimring, 2010; Chen et al., 2003; Haupt, 2018) have found that designers tend to make more lateral than vertical transformations, reducing the chances of designers making early fixations (Chen et al., 2003; Goel, 1995; Rodgers et al., 2000). However, there have also been studies (Song & Agogino, 2004) in which designers, in contrast, tend to make more vertical than lateral transformations.

In this study, I looked at how novice industrial designers’ hierarchical thoughts supported the way in which they generated design ideas, and how these ideas were laterally and vertically transformed during preliminary problem solving. Doing this, I could make recommendations for teachers to facilitate EGD learners’ design processes.

2.3 EXTENDED DESIGN COGNITION AS META-THEORY

Over the past few decades, there have been advances in cognitive behavioural theories, namely, Extended Cognition. The Theory of Extended Cognition recognises that designers extend their cognitive processes beyond their bodies (Clark & Chalmers, 2010). This is opposed to the Classical Information Processing Theory, which views design cognition as an internal cognitive process that isolates humans' cognitive behaviour from their external environment (Clark & Chalmers, 2010). Extending the mind into the physical environment results in accessible internal and external information sources, irrespective of their level of expertise or domain (Clark & Chalmers, 2010; Shani, 2013; Visser, 2004). These information sources constantly emerge from a designer's internal conception or external perception of the environment, which is expressed through their verbal utterances and visual representations. It is assumed that these expressions represent content of internal processing of information and the transformation thereof (Craig, 2001; Haupt, 2018), which I am interested in. In this study, I therefore adopted a meta-theory that is embedded in an Extended Design Cognition theoretical approach (Blom et al., 2018). This was originally developed by Haupt (2015), who integrated principles of ecological psychology (Anderson, 2003) with Newell and Simon's (1972) classic Information Processing Theory of designing. The benefit of following an integrated model of design cognition is based in its descriptive power for describing the development of designers' moment-to-moment design activity, as favoured by Clark and Chalmers (2010). The meta-theory consists of three inseparable components, namely, the extended information processing system, extended design problem-solving space and the extended design task environment. These components are discussed in the following sections.

2.3.1 Extended information processing system

An extended information processing system refers to a human problem solver (designer) capable of cognitive behaviour (Goel & Pirolli, 1992; Newell & Simon, 1972). This processing takes place during the early cognitive phases of the design process (discussed in Section 2.4). During these cognitive phases, the extended information processing system involves three structures, that is, an input, transformation process and output. An assumption pointed out by Blom and Bogaers

(2018) is that extended problem-solving behaviour is reliant on an input of information from either an internally conceived understanding or externally perceived stimuli regarding a situation. This information is systematically transformed into a physically embodied solution output, which might be represented as written texts, sketches, physical models or artefacts. These three structures correspond with the information processing systems' mental states, which shapes the extended design problem-solving space.

2.3.2 Extended design problem solving space

The extended problem solving space is seen as a modelling space that consists of designers' mental states (Goel, 1995). The mental states, namely, the start, mediating and goal states, determines the boundaries of the design problem-solving space. Design cognition scholars, including Blessing and Chakrabarti (2009), Cross (2011) and Lawson (2006), generally acknowledge that these mental states are characterised by an overall lack of information, which is due to the ill-structuredness of design problems.

The start state signifies the mental state where designers are presented with a design task (Goel, 1995; Haupt, 2018; Newell & Simon, 1972).The design brief of the given task often contains insufficient information about the problem (Cross, 2001b; Simon, 1996; Vincenti, 1990) and as such, designers generally experience uncertainty. This therefore compels them to engage in cognitive processes to understand the problem and propose solutions, resulting in the mediating states.

The mediating states signifies the mental states that mediate between the start and goal state, and contains limited information regarding the solution path (Cross, 2001b; Simon, 1996). The mediating states represents designers' need to supplement information missing from the given design brief and the dynamics between their meaning-making of information and proposing of solutions (Haupt, 2018; Simon, 1973). In this regard, designers therefore interact with internal and external information sources in order to generate and develop suitable solution outputs whilst constructing and manipulating physical external representations. This enables designers to engage in a transformation process, allowing them to transform from the start state to the goal state (Goel, 1995; Ullman, 2009). In this study, I focused on the mediating states in which designers' hierarchical thinking and idea transformations occur. In this regard, I looked at how the participants made lateral and vertical transformations between the mediating states, and how these transformations were supported by their hierarchical thinking.

The goal state, as the final mental state, is where designers commit and decide on a suitable design solution (Haupt, 2018; Newell & Simon, 1972). During the start and mediating states, the goal state consists of almost no information regarding the solution (Cross, 2001b; Simon, 1996; Vincenti, 1990), but as the designers progress with the design task, they make decisions, resulting in narrowing the problem-solving space. This means that at the beginning of the design process, designers have a vague understanding of the problem and the solution. Engaging with internal and external information sources enables designers to explore the problem space through constructing and manipulating their physical external representations, and make decisions structuring the problem-solving space (Goel, 1995; Haupt, 2018; Ullman, 2009). As a result, the goal state signifies a defined solution that could solve the ill-structured problem in the start state, and is typically embodied in designers' physical external representations.

The implication of the extended problem solving space for this study is that novice industrial designers think hierarchically during the mediating states. Their hierarchical thoughts result in them making lateral and vertical transformations of their initial ideas in order to propose suitable solutions for the goal state.

2.3.3 Extended design task environment

The extended task environment, originally proposed by Newell and Simon (1972), indicates an abstract structure that corresponds to a problem. An extended design task environment is described as an environment in which human problem solvers operate and interact with an external environment that is inclusive of the problem (Goel & Pirolli, 1992; Haupt, 2018). Forming part of the task environment is what designers know and what information sources they can access, and how they cognitively engage in accessing and utilising this information. Whenever designers encounter an ill-structured problem, the assumption is therefore that they use both internal and external sources of information to assist them in defining and solving the design task.

This implies that designers intentionally act on internal and external information sources during the course of the early cognitive phases of the design process (Anderson, 2003; Haupt, 2018). Internal information includes designers' prior experiences and domain-specific knowledge, whereas external information consists of external physical information sources. External information sources typically include sketches, 3D models, written text, diagrams, photos, reference books and the design client, which are further elaborated on in Section 2.5. For this study, internal and external information sources allow designers to intentionally fill the gap of the insufficiently specified information in the design brief.

2.4 Early cognitive phases of the design process

The distinct cognitive phases inherent in the design problem-solving space (Goel, 1995) are the problem structuring phase and the preliminary design phase of the problem-solving phases. Due to the general lack of information in the mental states, as discussed in Section 2.3.2, these phases are considered to be relatively vague and uncertain. This implies that during these phases a critical step exists in the problem-solving space, which means that designers typically attempt to find coherence among a range of known and unknown information sources from the design task environment (Cross, 2001b; Goel & Pirolli, 1992; Haupt, 2015; Liikkanen & Perttula, 2009). According to Goel and Pirolli (1992), the nature of information during the early phases of the design process will influence what designers do and why they do it in a particular way. This results in designers' need to find information to supplement unspecified information in the three mental states (Goel & Pirolli, 1992) in order to help them develop suitable solutions to the ill-structured problem. In the following sections, I discuss the two distinct cognitive problem-solving phases, and how these phases in some cases overlap with one another.

2.4.1 Problem structuring phase

Problem structuring is the process in which designers search for missing information about the problem in the provided design task and use the information to construct the problem space (Goel, 1995; Haupt, 2013; Simon, 1973). This implies that designers attempt to understand the problem they need to solve by discovering what the scope of the problem is and what its requirements and limitations are (Goel & Pirolli, 1992).

Designers therefore draw upon various internal and external sources of information, which includes recalling prior experiences and discipline-specific knowledge from memory. They also recall the information that they obtained using the extended design task environment to align their thoughts with the design brief (Goel & Pirolli, 1992; Schön, 1984). In this regard, the problem structuring by itself is not only believed to be a problem-solving activity, but also involves a set of four features that aim to provide insight into numerous sub-problems with which designers engage (Goel, 1995; Mitcham & Holbrook, 2006). The first feature is the aspects that designers consider in which they make statements about people, the purpose of the artefact, and resources (Goel, 1995). This indicates that problem structuring is associated with understanding what the artefact needs to do and how the artefact may be used. The second feature is the sources of knowledge wherein designers continuously refer to the client and the design brief as primary resources of knowledge in order to provide new information to the problem space (Goel, 1995). The third feature is the level of commitment that designers have to particular outputs, to which they typically make frequent verbal comments about particular design decisions without necessarily committing to any of them, as they are still in the process of gathering information about various solutions (Goel, 1995). The fourth and last feature is the distribution of operators that designers have during the problem structuring phase, for example, there is a high rate of 'add' and 'propose' operators (Goel, 1995). Designers typically make 'add' statements about how the problem can be defined and make 'propose' statements in order to give structure to the problem space.

These four features point out designers' intentions to redefine the ill-structured design task given to them by setting boundaries and selecting particular elements that are relevant for solving the problem (Love, 2002). In this way, designers gain insight into the nature and scope of the problem and attempt to establish coherence in the design problem space (Bickhard, 2008). I did not focus on the problem structuring phase, however, it is important to mention that the problem structuring phase leads to the problem-solving phases in which the focus of this study took place.

2.4.2 Problem-solving phase

Problem solving is a process in which designers engage in generating and exploring solutions that emerge from the problem structuring phase. Problem solving, like problem structuring, involves a set of five features. The first feature is the aspects that designers consider in which they make statements about the structure, behaviour and function of their envisaged artefact (Goel, 1995). This indicates that designers are attempting to find an optimum fit between the function and behaviour and an appropriate structure for the artefact (Kroes & Meijers, 2006). The second feature is the sources of knowledge to which designers continuously refer. There is still some input of the primary sources of information, however, this input of information tends to decrease rapidly when designers are gaining an understanding of the design problem (Goel, 1995). The third feature is the level of commitment that designers have to particular outputs, to which they start to become committed when their verbal comments are being transformed into externalised outputs (Goel, 1995). For example, this indicates that designers typically become committed to their emerging design when they graphically (sketching) and physically (modelling) externalise their design ideas. The fourth feature is the level of detail represented in designers' verbal and visual externalised outputs, which is typically of a higher degree of explicitness (Goel, 1995). The fifth and final feature is the transformation of the idea to which designers make lateral and vertical transformations (Goel, 1995). During the problem solving phases, designers iteratively adapt their design behaviour by changing the direction of their transformations laterally and vertically (Goel, 1995). This involves many backward and forward movements whereby designers make many unusual and unpredictable links between new and old information (Goel, 1995). This implies that designers in the transformation process will transform back and forth until their design ideas become suitable for the current problem.

Due to the size and complexity of design problems (Goel, 1995), the problem-solving phase is further differentiated into three sub-phases, namely, the preliminary design, refinement and detail design phases (Goel & Pirolli, 1992). During the preliminary design phase, designers typically generate and explore alternative solutions, which, according to Goel (1995), are under-developed ideas. These under-developed ideas incrementally transform as designers generally make more lateral than vertical transformations. Due to the large number of lateral transformations, designers' externalised solution outputs are course, and therefore their level of commitment is relatively low (Goel, 1995). During the refinement and detail design phases, designers typically elaborate and further a solution output while making detailed statements to specify and finalise their design idea. Designers' attention to detail during these phases, according to Goel (1995), is more structured and concrete in nature and allows them to make vertical transformation. Due to the increase of detail from vertical transformations, designers' level of commitment to their externalised solution outputs is relatively high (Goel, 1995).

In this study, I only focused on the preliminary design phase in which novice industrial designers generate and explore alternative solutions. It is during this phase that I looked at how novices' hierarchical thinking support the way they make lateral and vertical transformations. In this way, I was able to develop some pedagogical guidelines for EGD teachers to facilitate their learners' design processes.

2.4.3 Leaky modules

During the early cognitive phases of the design process, many researchers (Dorst & Cross, 2001; Goel, 1995; Visser, 2006) observed that the cognitive phases of problem structuring and problem solving constantly overlap with one another. Goel and Pirolli (1992) labelled this occurrence as 'leaky modules'. Leaky modules occur when designers engage in activities to search for missing information about the problem while focusing on generating design ideas and developing suitable solutions. As such, leaky modules support the notion of co-evolution, that is, a designers' understanding of the problem co-evolves with their understanding of the design solution (Dorst & Cross, 2001). A designer's responsiveness to new information during the actual process of problem solving is known as problem-solving triggers (Visser, 2006). These triggers are typically sparked by information perceived from the external environment and how it aligns with designers' internal information (Shani, 2013). The back and forth movement between the phases implies and contributes to the iterative nature of the design process. In this study, I did not look at how novice industrial designers move between the problem structuring and problem-solving phases. However, it is important that I acknowledge that leaky modules exist in any design activity.

2.5 PHYSICAL EXTERNAL REPRESENTATIONS

Physical external representations are designers' externalised thoughts in an extended design problem-solving space (Goel & Pirolli, 1992), and are represented as designers' two-dimensional (2D) and three-dimensional (3D) visual outputs. These represent their internally and externally processed information and typically take the shape of sketches, physical models or artefacts. According to the concept simulation framework for Industrial Design (Brand, 2018), designers typically make sketches characterised as quick and roughly drawn as well as mock-ups characterised as quickly made, low-resolution physical models during the preliminary design phase.

For the purpose of this study, I reviewed literature about how designers make physical external representations, specifically sketches and physical models. In the following sections, I discuss sketches and physical models by addressing their physical characteristics, as well as the roles these play in designers' design cognition. I also discuss how experts and novices use sketches and physical models, along with their involved thinking processes.

2.5.1 Sketches

In the literature, sketching is often referred to as a process of graphical thinking or graphical language, which designers use to maintain a dialogue with themselves and others (Stones & Cassidy, 2010; Yang & Cham, 2007). Sketches are made by hand using a device of various kinds (Babapour, 2016; Bertoline & Wiebe, 2011), which does not necessitate explicit quality (Yang & Cham, 2007). This means that sketching during the early cognitive phases of the design process does not require the application of specific drawing skills, but only the ability to represent the content of their thoughts, enabling them to communicate with themselves and with others. Outlining their thoughts, they typically use contouring lines (Bertoline & Wiebe, 2011; Caborn, Cave, & Mould, 2014). This implies that each line that designers make represents some information about the content of their thinking process. In turn, each line drawn by the designers influences their own thinking about the design solution. In this regard, the physical characteristics of sketches are abstract, vague, rough, ambiguous and lack detail to support the internal-external dynamics inherent in the design thinking process (Booth, Taborda, Ramani, & Reid, 2016; Goel, 1995; Hornecker, 2007; Visser, 2006). Figure 2.1 illustrates the nature of designers' rough sketches.

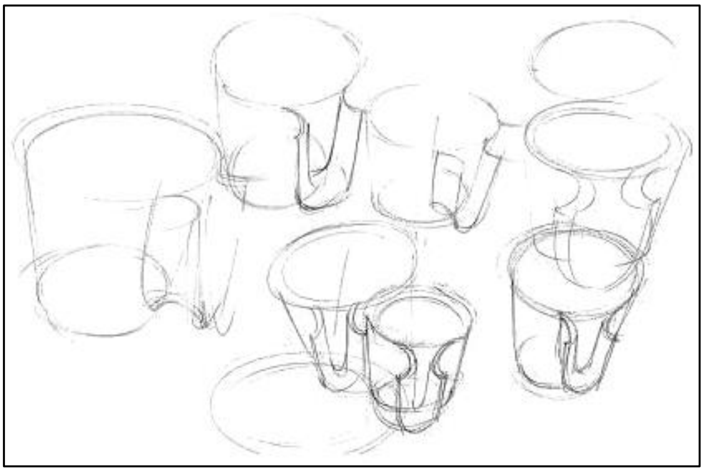


Figure 2.1: Example of quick and roughly drawn sketches

Figure 2.1 illustrates the roughness of detail represented in sketches, however, the amount of detail of designers’ sketches differ and is dependent on their mental state (Haupt, 2013) and changes during the course of the cognitive phases of problem solving. This implies that when designers experience uncertainty or have limited information about the design solution, their sketches tend to be rough, vague and abstract. As their thinking develops about the design problem and solution, the sketches become more specific and concrete, demonstrating the transformation of their understanding about the design problem and solution. This means that during the problem structuring phase, designers experience uncertainty, and therefore make sketches while searching the task environment for information not evident in their ill-structured design task. During these early phases, sketches serve designers by playing various roles, namely, physical, sensory and cognitive roles (Babapour, 2016). Table 2.1 outlines these roles further.

Table 2.1: The roles of sketches according to Babapour (2016)

	Sketches
Cognitive roles	**Thinking aid:** Sketches enable designers to think of different issues and aspects of the ill-structured problem. **Memory retrieval aid:** Designers monitor their thoughts by inspecting the sequence of sketches. **Support imagery:** Due to the abstract nature of sketches, sketches provoke mental imagery and enable designers to make changes. **Selective attention:** Sketches enable designers to selectively attend to parts of the design task. **Interpretation and emergence:** Sketches provoke the emergence of new ideas, which enables them to see things in new ways and recognise unintended consequences.
Physical roles	**Embodiment:** Sketches represents the embodied content of designers' thinking processes. **Radical transformation:** Designers move from one idea to a slightly different alternative idea by making radical changes to their sketches, showing their uncertain state. **Incremental transformation:** Designers transform from one idea to a more detailed version of the same idea by making incremental changes to their sketches, showing their more certain state. **Shape determining systems:** Sketching encourages certain shapes and ways of working. **Integration of visual and verbal data:** Speaking while sketching provides information about designers' thinking processes. **Integration of 2D and 3D perspectives:** Sketching in different views and dimensions allows designers to define their thinking. **Immediacy:** Sketching enables designers to become directly involved with the task environment, where they interact with information graphically in a transformation process.
Sensory roles	**Visual aid:** Sketches display designers' thinking visually, enabling them to inspect their work.

Table 2.1 lists the physical, sensory and cognitive role that sketches play in design cognition, according to Babapour (2016). For this study, I only focused on interpretation and emergence, radical transformation, incremental transformation and immediacy. I investigated how novice industrial designers' hierarchical thinking supports the way in which they laterally and vertically transform their design ideas, which is embedded in sketch-making.

There is much focus in the literature on the cognitive role of sketches of both experts and novices (Goel, 1995; Suwa & Tversky, 2002; Tversky, 1999). The literature clearly states how designers utilise sketches and the outputs of their sketching activities to assist their problem structuring and problem-solving processes (Cross, 2001a; Goel, 1995; Haupt, 2015; Lawson, 2006). In a literature review study, Cross (2004) indicates that experts' and novices' design expertise during the design process differs significantly. Experts tend to use explicit decomposing strategies while making sketches, attempting to recognise underlying patterns, and continuously evaluating their thoughts. In contrast, novices typically use trial-and-error techniques while making sketches to focus on and explore surface features of the problem in-depth (Cross, 2004, 2011). This implies that novices tend to occasionally get lost in gathering information, and they therefore typically generate and evaluate multiple ideas in a short time.

For this study, it is accepted that novice designers typically make sketches to physically externalise their hierarchical thoughts while making lateral and vertical transformations during the preliminary design phase. Sketches are therefore seen as a physically external embodiment of novice designers' hierarchical thinking, representing their transformation of ideas. I also believe that the nature of the externalised sketches influence the internal structure of designers' thoughts, as postulated in Extended Design Cognition theories (Clark & Chalmers, 2010; Visser, 2006)

2.5.2 Physical models

In the current literature, producing physical models is characterised as designers' process of constructing a physical and tangible format of their design ideas (Agogino et al., 2016). Physical models are usually made during the early cognitive phases of the design process (Kim & Lee, 2016; Majumdar, Fischer, & Schwegler, 2006; Qin, Wright, Kang, & Prieto, 2006; Viswanathan, Atilola, Esposito, & Linsey, 2014). In this way, the physical characteristics of physical models are rough, abstract and open-ended 3D representations of designers' ambiguous and undecided thoughts (Hornecker, 2007; Keller & Stappers, 2001), as illustrated in Figure 2.2.

Figure 2.2: Example of quick and roughly made physical models with cardboard

Figure 2.2 illustrates the rough representation of physical models. Designers use physical models during preliminary problem solving with the aim of transforming the level of certainty inherent in their mental states. This means that designers experience uncertainty, and therefore they engage with making physical models in order to explore and develop an understanding of a given ill-structured design problem (De Vries, 2013), which also results in structuring the problem space (Bertoline & Wiebe, 2011; Keller & Stappers, 2001; Kim & Lee, 2016; Majumdar et al., 2006; Qin et al., 2006). During the problem-solving phases, designers experience less uncertainty, and therefore transform their sketches into a tangible form to find suitable solutions that might solve the ill-structured problem. Therefore, physical models help designers to transform their uncertain mental state of mind to that of certainty (Agogino et al., 2016; Brandt, 2007; Keller & Stappers, 2001; Österman, Berlin, & Bligård, 2016).

Over the past decade, some literature has suggested the practical value of making physical models to limit sunk costs. Sunk costs refers to designers' devotion to the selected course of action in the fear of the loss of the cost sunk into the current path (Viswanathan & Linsey, 2011). The term 'cost' may refer to time, funds or effort spent in the current course of action. Limiting sunk costs, designers typically make physical models using cheap and manipulative materials, such as cardboard, wax, modelling clay, wood and foam (Bertoline & Wiebe, 2011; Keller & Stappers, 2001; Majumdar et al., 2006). As such, the limitation of sunk costs in physical models involves abstraction. This means that designers intentionally and unintentionally experiment with aspects of temporal reality, such as size, scale and texture (Goel, 1995). Typically, they engage with the problem in its contextual environment from which they draw embodied information that assists them to organise and structure the ill-structured design task

(Goel & Pirolli, 1992). This suggests that designers use physical models to uncover flaws in their design not visible in sketches, which therefore reduces the possibility of fixating unsuitable ideas (Hornecker, 2007; Viswanathan et al., 2014; Viswanathan & Linsey, 2011, 2012). Therefore, like sketches, physical models serve designers by playing a physical, sensory and/or cognitive role. These roles are outlined in Table 2.2, according to Babapour (2016).

Table 2.2: The roles of physical models according to Babapour (2016)

Physical models	
Physical roles	**Thinking aid:** Physical models enable designers to think about the ill-structured problem. **Memory retrieval aid:** Kinaesthetic memories are triggered with regard to materials and functional issues in order to make theoretical assumptions. **Learning aid:** Making physical models helps designers to understand by spending time on identifying problems. **Selective attention:** Physical models enable the selective attention to parts of the design task. **Interpretation and emergence:** Physical models enable reflection, interpretation and discovery.
Sensory roles	**Embodiment:** Physical models represent embodied content of designers' thinking processes that was originally contained in their sketches. **Incremental transformation:** Designers transform from one idea to a more detailed version of the same idea by making incremental changes to their physical models, showing their level of certainty. **Integration various components:** Designers typically build separate components from different materials, and then assemble all the components into one whole.
Cognitive roles	**Visual aid:** Physical models display designers thinking processes in a tangible format, which enables them to inspect their work from different views and perspectives. **Tactile aid:** Designers respond to physical behaviour through providing feedback when interacting with the physical models. **Other sensory aid:** Noise and smell help realising other dimensions of their design idea.

Table 2.2 lists the physical, sensory and cognitive roles that physical models play in design cognition, according to Babapour (2016). For this study, I only focused on thinking aid, selective attention, embodiment, incremental transformation and visual aid. I investigated how novice industrial designers' hierarchical thinking supports how they laterally and vertically transform their design ideas, which are constituted by physical modelling.

Previous studies have shown that experts' behaviour often differs from that of novices in significant areas while interacting with physical models. Experts are observed to make various physical models in all stages of the design process (Hilton, Linsey, & Goodman, 2015). Significantly, however, they tend to rely heavily on reducing complexity by making physical models to quickly test ideas and generate new ones during the early stages of design (De Beer, Campbell, Truscott, Barnard, & Booysen, 2009; Gerber, 2009). Novices, alternatively, generally consider physical models to be made towards the end of the design process as a process to test and evaluate, and do not see physical modelling as a dynamic tool to help generate and develop design ideas (Hamon et al., 2014). Studies show that novices express difficulty in understanding the problem when visualising their thoughts through only sketch-making (Ahmed, Wallace, & Blessing, 2003; Welch, 1999). This therefore indicates the need and importance of them visualising their thoughts in a physical format. This implies that novices struggle to organise their thinking patterns to be able to understand and structure an ill-structured problem. Therefore, like with sketches, there is even less literature regarding the way in which novice designers' think while making physical models.

For this study, novice designers, in addition to sketches, are considered to typically make physical models to physically externalise their hierarchical thoughts while making lateral and vertical transformations during the preliminary design phase. Physical models are therefore seen as a physically external embodiment of novice designers in which they explore their hierarchical thinking through sensory stimuli in order to represent their idea transformations. Their interaction with the external stimuli in turn facilitates the development of their idea transformations.

2.6 Conceptual framework

As discussed in Section 2.2.1, various models exist for investigating the hierarchical thinking of designers. I adopted the hierarchical thinking model developed by Haupt (2018) as the conceptual framework for this study. Utilising and adopting Haupt's (2015) model of hierarchical thinking seemed to be in line with this study's focus on investigating how hierarchical thinking supports the idea transformations of novice industrial designers. Even though this model is based on expert designers' design thinking, it was effectively employed in a study conducted on novice designers

(Dubery, 2015), which therefore made it appropriate for this study. One way of investigating how hierarchical thinking supports idea transformation is through the lens of Extended Design Cognition, which is embedded in this conceptual framework.

Haupt (2015) argues that her model of hierarchical thinking not only augments the Theory of Extended Design Cognition, but also enhances the understanding of how designers effectively search for suitable solutions that align coherently with their various design intentions. These intentions, in the form of four hierarchical thinking levels, range from abstract aspectual intentions to subsequently more concrete functional intentions, physical elements and implementation intentions. During designers' hierarchical thoughts, they undergo unbiased and subsequent moments of insight in which they use abstraction to frame possible solutions by anchoring their abstract intentions in relevant subsequent intentions (Haupt, 2018). This implies that designers would typically make physical external representations in the external environment to move between the different hierarchical levels of intentions.

In this regard, selecting and adopting this model for my conceptual framework allowed me to examine the way in which novice designers think while they generate and transform their design ideas through making physical external representations. Figure 2.3 illustrates the conceptual framework utilised in this study.

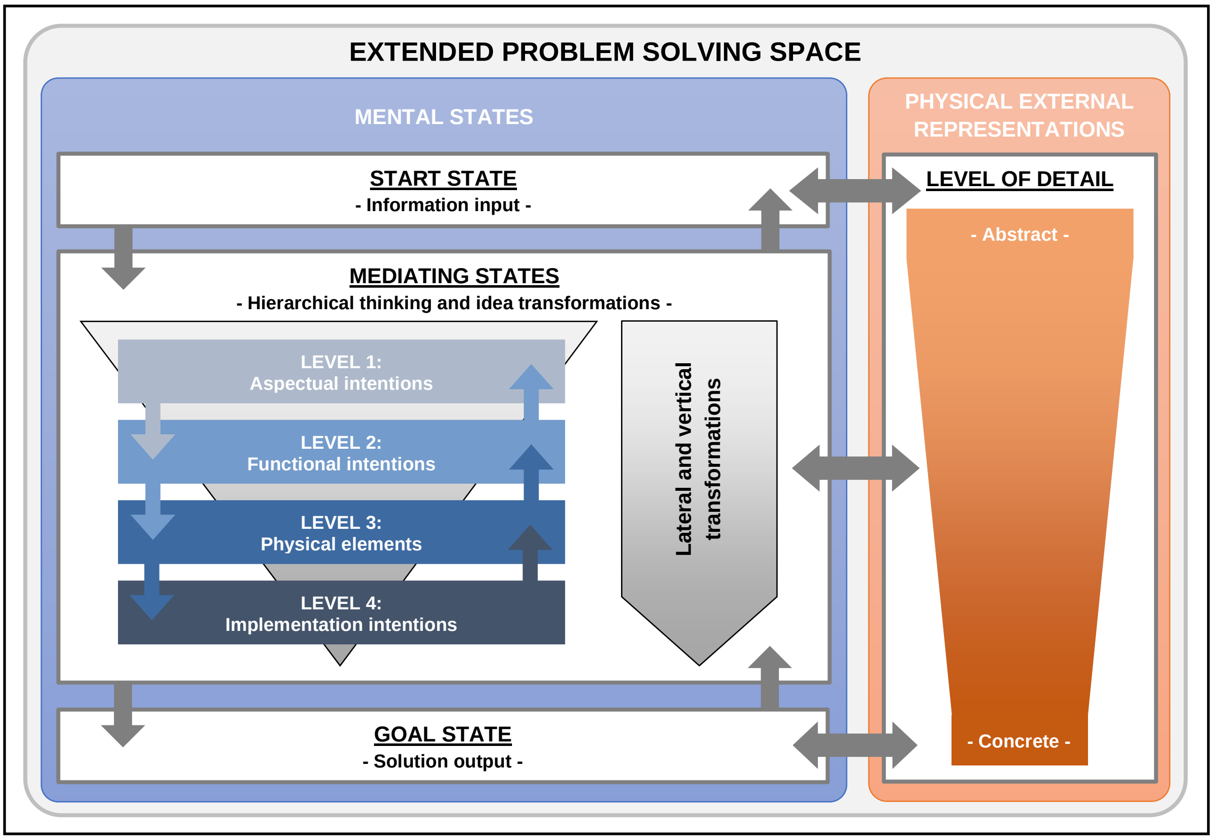


Figure 2.3: Conceptual framework: Hierarchical thinking and idea transformation during the preliminary design phase, adopted from Haupt (2018)

Figure 2.3 illustrates the conceptual framework of this study, which was adopted from Haupt (2018). The conceptual framework works in a top-down manner and falls within the extended problem-solving space, which consists of designers' mental states and the physical external representations that they make. Designers' mental states consist of three states, namely, the start, mediating and goal states, as discussed in Section 2.3.2. This study focused on the mediating states where designers engage in processing information from internal and external sources to supplementing the lack thereof in the given design brief (Simon, 1973). In this regard, both designers' hierarchical thinking and idea transformations are embedded within the mediating states. Below, I describe novice industrial designers' hierarchical thinking and idea transformations, however, the procedure that I used in which I traced their intentions is described in Section 3.7.1.

In terms of hierarchical thinking, according to Haupt (2018), designers' levels of intention start with aspectual intentions (level 1), which is followed by functional intentions (level 2), physical elements (level 3) and implementation intentions (level 4).

The first hierarchical thinking level of the conceptual framework, aspectual intentions, consists of qualitative abstractions (Basden, 2000), which are seen as distinct design aspects. Design aspects are assumed to give meaning and direction to how designers select and transform their design ideas, as well as how they commit to some ideas and reject others (Haupt, 2013). In other words, aspectual intentions are abstract thoughts that serve as an overarching guiding mechanism or anchor point for framing designers' thoughts when making connections with the subsequent levels of hierarchical thinking (Haupt, 2018). Various authors have identified different kinds of design aspects in a design cognition context (Goel & Pirolli, 1989; Searle, 1983; Tversky, 2005). However, Haupt (2013) labels design aspects as 'aspectual intentions', which are based on Dooyeweerd's Theory of Aspects of Temporal Reality in which he identified 15 aspects (Basden, 2000). A summary of Dooyeweerd's aspects of reality is provided in Appendix G1. Designers view these design aspects as topics that are important to give attention to in a solution (Basden, 2011). As such, design aspects are seen as the content of designers' intentional states. When designers refer to a particular design aspect, their knowledge regarding the design aspect is typically implied and not necessarily explicated (Haupt, 2018). This suggests that the designers could choose when to follow and apply the governing laws of particular aspects, and when to disregard them without rejecting their validity.

At the second level of hierarchical thinking, functional intentions, designers typically seek to define the functional nature of an artefact's purpose. Artefacts in general are seen as physical objects meant to do things in relation to designers' desired intentionality (Franssen, 2008). Functional intentions, according to Haupt (2018), are triggered by designers' attention to specific aspectual intentions, in which they explore functionality and derive the functional requirements expected to be achieved in a design solution (Goel, 1995; Haupt, 2018). This implies that functional intentions are more concrete compared to abstract aspectual intentions (Haupt, 2013). However, functional intentions can be reformulated during the design process (Haupt, 2018), which therefore means that functional intentions are semi-concrete thoughts. In order to understand designers' formulation and reformulation of functional intentions, I traced utterances in which both aspectual and functional statements occur.

The third hierarchical thinking level of the conceptual framework, physical elements, consists of designers' statements regarding the physicality of the artefact that they are designing. Physical elements are thoughts comprising geometrical descriptions about the physical makeup of their envisaged artefact. Physical elements could include thoughts about objects, components and lower-order properties, such as a handle, wheel, clamp, edges, flanges, grooves, shape, size, colour, material and texture (Kroes, 2006). Making statements about physicality, designers attempt to provide their functional intentions with a physical structure. Designers typically aim to achieve a dual nature in their envisaged artefact, which implies the designer's need to find an optimum fit between physical elements and their intended function (Kroes & Meijers, 2006). In this way, designers attempt to further transform their abstract aspectual intentions and semi-concrete functional intentions into concrete expressions about physical elements.

The fourth and final hierarchical thinking level of the conceptual framework, implementation intentions, consists of the choices that designers make which they think will support them in meeting the requirements expected to be achieved (Haupt, 2018). Implementation intentions serve as designers' saturation point in their hierarchical thinking process (Haupt, 2018) where the physical elements of their envisaged artefact meets with their functional intentions and, by implication, aspectual intentions. Distinguishing intentions consisting of implementation thoughts is when designers refer to a specific activity, for example, 'you can put the blade on a disk, and it will cut in a circular motion'. This therefore implies that implementation intentions are more concrete than the preceding hierarchical levels, which enables designers to make propagated commitments to selected ideas (Gollwitzer & Schaal, 1998).

In terms of idea transformations, it is assumed that designers' transformation of ideas is supported by their hierarchical thinking process. According to Goel (1995), designers transform their ideas by making lateral and vertical transformations. Lateral transformations enable designers to transform from an existing design idea to a slightly alternative design idea (Goel, 1995). In this regard, the generation of alternative design ideas would indicate designers' intention to broaden their scope, as well as indicating their level of commitment to design ideas to be low. Vertical transformations enable designers to transform from an existing design idea to a more detailed version of the same design idea (Goel, 1995). In this regard, the detailing of design ideas would indicate designers' intention to deepen their scope, as well as indicating that their level of commitment to design ideas increases.

In terms of physical external representations, designers externalise their thoughts by means of quick and roughly made sketches and physical models. The level of detail of designers' physical external representations during the preliminary design phase differs and ranges from being numerous abstract representations of thought to fewer, more concrete representations of thought. In this study, I did not emphasise how novice designers' hierarchical thinking and idea transformations are embedded in the physical characteristics of their physical external representations. However, I paid attention to how their hierarchical levels of intentional thoughts developed to support idea transformations, which are embedded in their physical external representations.

2.7 Conclusion

In this chapter I provided an overview of design cognition in the field of Industrial Design. Thereafter, I discussed the meta-theory of Extended Design Cognition, which I employed for its descriptive power in describing the development of novice industrial designers' design activity during the early cognitive phases of the design process. Furthermore, I discussed previous studies that focused on the role that physical external representations play in novice designers' design cognition. I concluded this chapter by presenting and discussing the conceptual framework of this study, which is based on Haupt's (2018) Model of Hierarchical Thinking. In Chapter 3, I discuss and explain the methodological implications of examining the participants' hierarchical thinking and how it supports their idea transformations during the preliminary design phase.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 INTRODUCTION

In Chapter 2, I discussed the theoretical underpinnings of cognitive theories, which served as the theoretical foundation for the way in which I planned to conduct this study. These underpinnings enabled me to study novice industrial designers' hierarchical thinking processes during the preliminary design phase.

The purpose of Chapter 3 is to align the methodological choices with the purpose of this study and the research questions stated in Chapter 1. I start this chapter by discussing the selected research paradigm, approach and design of this study. Thereafter, I explain the sampling procedure and selection criteria, followed by an explanation of the data generation and analysis process. I conclude this chapter by discussing the quality assurance measures taken and the ethical guidelines I adhered to.

3.2 PARADIGMATIC APPROACH

The paradigmatic approach, as embedded in this study and which is defined as a basic set of beliefs that guides a researchers' actions (Denzin & Lincoln, 2017), is informed by critical realism. Bhaskar (1975) stated that critical realism as a research paradigm is concerned with studying the observable and unobservable structures, mechanisms and interactions in reality in order to explain the occurrence of a given set of events (Wynn & Williams, 2012). Wynn and Williams (2012) further explain that when researchers take a critical realist stance, they are able to develop in-depth explanations when studying these structures, mechanisms, interactions and events. In this study, this implied that I could describe novice industrial designers' hierarchical thinking events whilst they were transforming their ideas. I did this by studying how the designers interacted with and utilised internal and external information sources during design problem solving.

A paradigmatic approach is further governed by a framework of assumptions, namely ontology, epistemology and methodology, which function as a lens through which meaning is made of what researchers believe to be true (Creswell, 2014). This study is based on these assumptions, as supported by Danermark et al. (2002) and Wynn and Williams (2012). These assumptions are discussed further in the sections below.

3.2.1 Ontological assumptions

Critical realism adopts a transcendental realist ontology (Bhaskar, 2013), which accepts that reality exists independently of our knowledge about it (Easton, 2010; Wynn & Williams, 2012). This means that reality is constituted by structures, mechanisms, interactions and events, and how these structures, mechanisms, interactions and events really work (Bhaskar, 2013; Easton, 2010). Critical realism therefore allows researchers to study both unobservable and observable phenomena (Easton, 2010; Wynn & Williams, 2012). In this regard, the ontology of this study involves internal (unobservable) and external (observable) realities of the teams of designers and their design processes. Designers access information in the design task environment, which can be done either internally (the recollection of memory) or externally (their perception of the physical environment) as they attempt to structure and solve a given design problem (Kirsh, 2009).

Furthermore, critical realism involves a stratified nature of reality (Nash, 2005), which means that elements grounded in a particular mechanism might be grounded in another mechanism. However, the elements from which the mechanism originally emerged cannot be excluded (Scott, 2013). It is argued that if the elements are excluded from which it originally emerged, then what is the point of having different mechanisms with independent 'powers' (Nash, 2005). In this research, I focused on how novice industrial designers' mechanisms (various hierarchical intentions) emerged as they interacted with structures (internal and external information), and how these mechanisms supported their events (lateral and vertical transformations).

3.2.2 Epistemological assumptions

Critical realism adopts a relativist epistemology (McEvoy & Richards, 2003), which accepts that our knowledge of the real world is fallible (Easton, 2010; Sayer, 1992). This means that our understanding of reality is incomplete and subjective (Easton, 2010). However, critical realism is thus founded on the necessity that researchers employ *a-priori* theoretical constructs in order to 'judge' what is true (Fletcher, 2017;

McEvoy & Richards, 2006). In this regard, the epistemology of this study was shaped by the conceptual framework discussed in Section 2.6, which was informed by *a-priori* theoretical constructs. As such, the *a-priori* theoretical constructs on which I focused were novice industrial designers' hierarchical thinking levels and idea transformations during the preliminary design phase. This allowed me to describe both objective and subjective elements of reality (Wynn & Williams, 2012), which included novice designers' internal world represented by their various levels of intentions and their external world, found in their extended design task environment (Goel, 1995; Haupt, 2013; Kirsh, 2009).

3.2.3 Methodological assumptions

Observation, according to Easton (2010), is fallible, which means that it is unlikely for a researcher to reveal a complete and full understanding of the structures, mechanisms, interactions and events underpinning design cognition phenomena through non-participatory observation. However, taking a critical realist point of view supports the need for collecting various types of data. I therefore was able to adopt a concurrent mixed methods approach allowing the generation of multiple qualitative and quantitative data sources. In this way, I was able to capture confirmatory instances of both participants' internal and external cognitive processes.

By generating both qualitative and quantitative data in this way, I subscribed to the notion of methodological triangulation (Abowitz & Toole, 2009; Bitsch, 2005). This comprises the use of multiple data collection and analysis methods instead of relying on only one data source. Triangulation falls under the quality assurance of this study, which is addressed further on in Section 3.8. The qualitative and quantitative nature of this study is discussed in the following section.

3.3 RESEARCH APPROACH

Based on this study's paradigmatic assumptions, informed by critical realism (discussed in Section 3.2), I engaged in a concurrent mixed methods research approach (Creswell, 2014; Tashakkori & Teddlie, 2010). This implied that I needed a combination of qualitative and quantitative approaches during the data generation and analysis to be able to address my research questions, as stated in Section 1.7. This study therefore was qualitatively dominant (QUAL + quan) (Creswell, 2014).

Following a concurrent mixed methods research approach implied that I simultaneously generated both qualitative and quantitative data (Maree, 2016; Tashakkori & Teddlie, 2010). The qualitative data consisted of verbal and visual data types, whereas the quantitative data consisted of temporal and sequential data. Due to the implicit nature of thinking, I was unable to study the participants' every thought (Ericsson & Simon, 1993). It was therefore important that I generate numerous data types that might show evidence of hierarchical thinking and idea transformations in order to address the research questions. Generating multiple data types concurrently helped me to provide a rich account of the participants' hierarchical thinking and idea transformation. As such, adopting a mixed methods approach seemed to best fit this study since I could capture multiple data types and engage in deeper levels of analysis, which a single method would not have allowed me to do (Creswell, 2014).

With regard to data analysis, conducting a study in this way provided me with the tools to focus on design cognition phenomena, specifically on novice designers' hierarchical thinking and the transformation of their ideas. It also allowed me to transform qualitative data into quantitative data in the form of frequencies of hierarchical thinking and idea transformation cognitive events.

3.4 RESEARCH DESIGN

In this study, I selected a single descriptive case study to be the most appropriate research design (Stake, 2018; Yin, 2014; Yin & Campbell, 2018). This allowed me to gain a deeper understanding of the internal processes of novice Industrial Design students during the early cognitive phases of the design process. My aim was to grasp how their hierarchical thinking processes supported the way in which they transformed their design ideas, which occurred as a result of their interactions with internal and external information. In this way, I was able to make contributions to the professional practice of EGD teachers, and make recommendations for design educators to facilitate students' design thinking processes.

I considered the case to involve the design cognition of the participants during the preliminary design phase in their natural Industrial Design learning environment. Furthermore, the case consisted of teams of third-year Industrial Design students as participants. I considered each team of participants to share similar problem-solving abilities. I decided to rather consider a collective case instead of individual cases in order to maximise verbal fluency among the teams. The participants' verbal utterances, according to Ericsson and Simon (1993), are only an "informationally equivalent representation" of their mind at that very moment. It can therefore be inferred that the content of a participant's thoughts is directly related to what they are saying, what they said earlier, and what they might say later on (Craig, 2001). Together with the verbal data, a case study research design allowed me to collect multiple data sources in order to provide in-depth descriptions of the case (Creswell, 2014; Yin, 2014). This seemed complimentary to critical realism, which supports the need to collect various data types (Easton, 2010). I was therefore able to generate verbal, visual and temporal data, which is further discussed in Section 3.6. These data types could also be analysed by integrating qualitative and quantitative approaches, which is outlined in Section 3.7. After analysing the different data types, it was required that I constructively interpret the participants' hierarchical thinking processes and idea transformations during the preliminary design phase of the design process (Creswell, 2014; Yin, 2014). In order to do so, the case was interpreted by continuously referring to the *a-priori* theoretical constructs in the conceptual framework of this study (discussed in Section 2.6).

Having framed the research paradigm, research approach and research design of this study, I was able to plan my data generation and analysis procedure. Table 3.1 presents the research process that I followed in order to address the research questions.

Table 3.1: The research process followed in this study

Phase 1:	**Initial exploration of the field**		
Strategies	**Approach**	**Purpose**	**Rigour**
Pilot study	**QUAL:** Collection of verbal data and visual data. **quan:** Temporal data.	Observing naturalistic industrial design learning environments and identifying practical and logistical challenges.	Rich contextual descriptions for transferability.
Literature survey		Investigating EGD CAPS document and prescribed textbooks. Extensive literature study on design cognition.	
Phase 2:	**Selection of participants**		
Strategies	**Approach**	**Purpose**	**Rigour**
Purposive sampling	The use of selection criteria.	Identifying top-achieving third-year students with the ability to communicate design ideas effectively.	Informed consent. Trustworthiness; Transferability; Credibility. Richness of data; Validity.
Phase 3:	**Concurrent data generation**		
Strategies	**Approach**	**Purpose**	**Rigour**
Concurrent in-vivo methodology	**QUAL:** Generation of verbal data and visual data. **quan:** Temporal data.	Observing the introduction of the design task to the participants. Observing participants' design behaviour elicited by the design task.	Ensure naturalistic instruction of the design task. Trustworthiness; Dependability; Credibility; Transferability.
Phase 4:	**Data structuring, analysis and interpretation**		
Strategies	**Approach**	**Purpose**	**Rigour**
Constructs from the conceptual framework	**QUAL:** Segmenting verbal data into utterances based on the content of thought processes. **quan:** Segmenting verbal data into temporal instances and calculating number of occurrences. **Mixed:** Merge data to reveal occurrences of hierarchical thinking and idea transformation.	Individualisation of utterances into cognitive segments for the investigation of participants' design cognition. Identifying observable evidence of *a-priori* theoretical constructs embedded in the conceptual framework: • Hierarchical thinking levels • Transformation of ideas	Limiting researcher bias. Maximising neutrality. Credibility. Confirmability. Validity.

Phase 5:	Reporting and dissemination		
Strategies	**Approach**	**Purpose**	**Rigour**
Constructs from the conceptual framework	**Mixed:** Narrative accounts of the participants' design processes.	Describing the participants' design cognition. Integrating QUAL and quan findings. Identifying patterns and themes.	Confirmatory triangulation. Researcher reflexivity. Trustworthiness.
Tables and graphic representations	Presenting the occurrences of participants hierarchical thinking processes. Presenting the occurrences of idea transformations.	Presenting guidelines for the effective facilitation of problem-solving strategies in the early phases of the design process.	Validity.

3.5 Sampling

In conducting this study, I used a purposeful sampling method to select the participants needed for this study. This non-probability sampling method allows building a sample that is satisfactory to the specific needs of a study (Cohen et al., 2018). By using this sampling method, I was able to select participants that provided me with the richest amount of information from which something could be learned (Check & Schutt, 2012; Merriam, 1998). This sampling method is common among the QUAL + quan mixed methods research approach and seeks to examine cases rich in information and in great depth about issues of central importance to the purpose of a study (Patton, 2008).

In this study, four third-year Industrial Design students from the Faculty of Engineering of a local university of technology in Gauteng were purposefully selected to take part in this study. Selecting third-year Industrial Design students, grounded on their academic performance of the previous year of study, is based on an expertise development case study in Product (Industrial) Design conducted by Popovic (2004), finding that domain-specific knowledge (knowledge in a particular field of expertise) and the ability to structure a problem are higher in third-year students than in first-year students. In novice design behaviour, it is known that they typically apply trial-and-error techniques when presented with a design problem (Ahmed et al., 2003). However, Popovic (2004) found that third-year students apply less trial-and-error techniques, which implies that the idea transformation in their physical external representations is more stable than with first year students.

To select third-year Industrial Design students, I focused on the higher performing students. Selecting top-achieving students was based on the idea that higher-order design cognition in tertiary education is more likely to be found in top-achieving students than in poorer performing students (Dubery, 2015). For this reason, I limited the sample of this study to four participants due to the large amount of information generally generated in cognitive research. Selecting a larger sample would make reporting impractical, which would therefore compromise the credibility of this study. I furthermore aimed to derive generic patterns of design thinking. I therefore did not consider individual differences between the participants.

Selecting Industrial Design students from a local university of technology in Gauteng enabled me to conveniently use their fully operational Industrial Design studios as a research site because of their technological background. The use of these studios assisted to ensure that the capturing of data was done in a naturalistic manner where the participants felt the most comfortable while engaging with a given design task (Carroll & Johnson, 1990). Ensuring a conducive environment for capturing data, I used selection criteria in order to select a non-discriminatory sample from which much could be learned, which is discussed in the following section.

3.5.1 Selection criteria for participants

To purposefully select a sample of four top-achieving third-year Industrial Design students, the input of the lecturer responsible for the subject Industrial Design II was required to identify and group students who were appropriate for this study according to similar academic performances. This was done in order to minimise the influence of distinctive individual differences, problem styles, and long- and short-term memory effects (Goel, 1995). The following criteria were used to select the sample of this study:

- Consistently being one of the top achievers in all of the design tasks given to them in the subject Industrial Design II.
- Students' ability to apply their knowledge and skills effectively to the design process for the subject Industrial Design II.
- Students' ability to verbalise their thoughts when engaged with the given design tasks for the subject Industrial Design II.

- Students' ability to use both critical (analytical) and creative (lateral) thinking strategies proficiently to resolve the diverse requirements of users and the environment, and the selection of appropriate materials and manufacturing processes for the subject Industrial Design II.

3.6 Data generation strategies

The data generating instrument of this study was a design task (discussed in Section 3.6.2), which I gave to the participants to solve. From the design task, the participants produced both qualitative and quantitative data. The data, captured on digital video recordings, provided me with verbal and visual (QUAL) information, as well as temporal (quan) information. This allowed me to map the participants' hierarchical thinking and idea transformation processes during the preliminary design phase of the design process. During the data generation, the participants simultaneously produced other physical external representations in the form of written texts, sketches and mock-ups. These physical external representations augmented the mapping process of the participants' hierarchical thinking and idea transformation processes (QUAL) and allowed the calculation of the number of occurrences of each hierarchical thinking level (quan).

In the following sections, I discuss the data generation setup of this study. I then discuss the data generation instrument, as well as the steps I took to capture the data for this study.

3.6.1 Data generation setup

I employed in-vivo methodology as the data generation setup (Christensen, 2005; Dunbar, 2001). An in-vivo methodology study was developed to study cognitive processes in scientific reasoning (Dunbar, 2000, 2001). The name is borrowed from biological sciences where, for example, bacteria can be examined in a host organism (in-vivo). This implies that cognitive processes can be examined as they occur in real-life situations through conversational dialogue analysis (Chi, 1997). Conducting this study using in-vivo methodology allowed me to investigate the participants' naturalistic cognitive processes and natural dialogue without specific instruction to think aloud (Ormerod & Ball, 2017). This study departs from conventional studies investigating the cognitive processes of designers through Think Aloud Protocols Studies (TAPS).

Researchers who employ TAPS typically follow a true-experimental approach, which requires the participants to be isolated and confined to laboratory conditions in order to free them from the necessity to communicate (Lincoln, Lynham, & Guba, 2011; Simon, 1996). However, I regarded such isolation of the participants as artificial and not reflecting the naturalistic manner in which contemporary design work takes place (Ormerod & Ball, 2017; Van Someren, Barnard, & Sandberg, 1994). In contrast with true-experiments, Haupt (2013) conducted a quasi-experimental protocol study in which she adjusted the environment in order to enhance the participants' natural behaviour.

In line with Haupt's (2013) approach, I also sought to observe the participants of this study, engaging with a given design task with their natural behaviour. However, differing from her study, my role as the researcher in ensuring a natural task environment was to act as a non-participatory observer and not to interfere with the participants' pace of thinking or generation and transformation of ideas. Furthermore, I did not provide the participants with an experimental setup of their usual design environment like Haupt (2013) did. Instead, I observed the participants where they usually engaged in problem solving activities, in their Industrial Design studios, without disrupting their natural work-flow. This implies that I considered this study as a case study without the conventional experimental setup. Conducting this study in this manner not only increased objectivity, which also falls in line with the critical realist paradigm (Cohen et al., 2018; Wynn & Williams, 2012), but also enabled me to develop some pedagogical guidelines for EGD teachers to facilitate learners' design thinking in a non-experimental environment. Having discussed the motivation behind the setup of the in-vivo methodology, I further discuss the strategies that I employed for the data generation process of this study.

3.6.2 Data generation instrument: The design task

A design task was used as the data generation instrument in this study. Ensuring the natural flow and way in which the Industrial Design studio is normally run, both the lecturers responsible for the subject Industrial Design II and Industrial Design III crafted the design task used for this study. However, there were a few requirements that the responsible lecturer had to keep in mind in order for the design task to be in line with this study, which are as follows: the design brief had to be of ill-structured nature, challenging, realistic and appropriate for the participants; allow students to work in pairs; allow the participants to actively communicate with one another; and motivate participants to produce physical external representations.

Conducting an in-vivo methodology study meant that I had to adhere to the responsible lecturers' requirements of the design task, which is called a Block project. The Block project comprised eight days, which had specific instructions that had to be completed by a set time each day. The design of the Block project allowed me to capture data for one of the eight days. The design brief required participants to *Design a hand-held or counter-top hand operative machine that is a cost-effective alternative to making Nespresso coffee pods* (refer to Appendix C1), that had to perform three stages. These stages were: Stage X (cutting aluminium foil blanks for the pod and lid), Stage Y (forming aluminium foil into pods with a lip) and Stage Z (sealing the lid into the pod once filled with ground coffee). The participants were confronted with limited information in all three states in the design problem spaces, namely: the start (input) state; transformation state; and goal state (Goel, 1995; Newell & Simon, 1972). The participants further had to access information from the various sources at their disposal, including the ill-structured design brief. The participants relied on internal information such as recalling generic experiential and domain-specific knowledge, and external information embedded in the physical environment. The participants' goal was to represent satisfactory solutions by transforming the information accessed through verbal utterances and concurrent visual representations to fully understand the requirements and scope of the problem, for which they only had approximately 5 hours to work on the given instructions for the observed day. To ensure credibility through triangulation and not to disrupt the natural flow and way in which the Industrial Design studio is run, the same design brief was given to all participants of the two pairs.

3.6.3 Steps in conducting in-vivo methodology

The in-vivo methodology consisted of four steps that enabled me to capture verbal and visual data simultaneously on digital video recordings (Goel, 1995; Haupt, 2013).

The steps that I followed were adapted from Haupt's (2013) method of conducting think aloud protocols.

Step 1: Preparing the setting

The first step involved preparing the setting to enhance effective elicitation of novice design cognition behaviour. As pre-arranged with the responsible lecturer, the participants' workstation in the open plan Industrial Design studio was situated separately from the rest of the students. The separation between the participants of this study and the rest of the students was due to practical reasons, namely: reducing non-participant interference; reducing background noise to accurately record verbalised design thinking; and ensuring a conducive environment for design problem solving. The participants' workstation included a computer with internet connection for each participant, a colour printer, as well as paper for printing or sketching, as shown in Photograph 3.1. As this study was a case study and not part of any experiment, the participants were allowed to ask any lecturer for advice and look at existing artefacts provided by the responsible lecturer for the Block project, which included (a) A Nespresso coffee machine, and (b) Nespresso coffee pods, as shown in Photograph 3.2.

Photograph 3.1: Photograph of the participants' workstation for the in-vivo methodology setting

Photograph 3.2: Photograph of the existing artefacts used for the Block project

In order to document the design behaviour of the participants, I employed a camera technician. The camera technician and I prepared the camera equipment in order to effectively capture the verbal and visual data. In this regard, four GoPro action cameras were attached to head mounting straps, with fully charged batteries inserted, and were attached to each participant on head mounting straps. Thereafter, the cameras were adjusted to each participants' own line of sight in order to record what they saw, what they interacted with, who they interact with, and how they interacted.

Step 2: Standard introduction to instructions

As standard practice for introducing the participants to the procedure, I provided them with the following instructions:

> *You are going to be addressed by your lecturer in a moment where he will give you the design brief. You are requested to return to your workstations immediately so that I can start the video recordings. Do not start with the Block project before the video recordings started. Once the cameras are recording, you are requested to read the design brief and perform the task in the way you normally would do in class. Please speak loudly. The video recordings will focus on capturing your words as well as your actions.*

Step 3: Introduction of the design brief

As standard practice in the Industrial Design studio, the responsible lecturer gathered the entire third-year cohort, including the participants, to take the attendance register. Thereafter, the lecturer introduced me to the third-year cohort and explained to them that I would be video recording the four students taking part in my study. He also stressed that the students that did not take part in my study should constrain themselves from disrupting the participating students. He then moved to introducing the Block project.

The responsible lecturer discussed the design brief in detail and provided the participants with the instructions of the day's task. This implied that all students had to complete their task by the end of the session, which gave them a total of five hours.

Step 4: Conducting the concurrent in-vivo methodology

The fourth and final step commenced after the physical interaction of placing the camera equipment on the participants' heads and the video recordings had begun. My role as a non-participatory researcher was to observe the participants' natural design behaviour, and not to provide any information or interfere with their pace of thinking or generation of ideas (Haupt, 2013; Lloyd, Lawson, & Scott, 1995). The participants engaged with the design task in pairs, which created a natural dialogue between them that enhanced the flow of their verbalised thoughts.

3.7 DATA ANALYSIS AND INTERPRETATION

After collecting the data through in-vivo methodology, the data analysis and interpretation of this study involved organising and describing the recorded audio and visual information in terms of the theory embedded in my conceptual framework (Figure 2.5). I derived this from the content of the participants' thoughts as represented in their verbal and visual data.

3.7.1 Data analysis

In order to analyse the data, I had to carry out extensive structuring of the verbal data set (refer to Appendix E). The data was organised in such a way that not only I was able to identify emerging patterns or connections (Goel & Pirolli, 1992; Haupt, 2013), but I was also able to reduce the data to manageable amounts without loss of complexity (Haupt, 2013; Tashakkori & Teddlie, 2010). The data structuring was, however, not separate from the data analysis, but essentially part of it. In this way, I adapted the Discourse Analysis methodology from Ash (2007), which enabled me to start with the data structuring and analysing procedure. The methodology consisted of three levels of analysis, namely, macro-analysis, meso-analysis and micro-analysis. Macro-analysis requires the researcher to provide an overview of the recorded audio visual data, creating a flowchart of the events that occurred. Meso-analysis requires the researcher to select segments significant to the study for further analysis. Micro-analysis requires a deeper analysis of the selected segments according to the context of the researcher's study. In order for this methodology to assist me, I adapted it by distinguishing the verbal (audio) data from the visual data, and by adding five sub-levels within the three levels of analysis. The adapted methodology is illustrated in Figure 3.1.

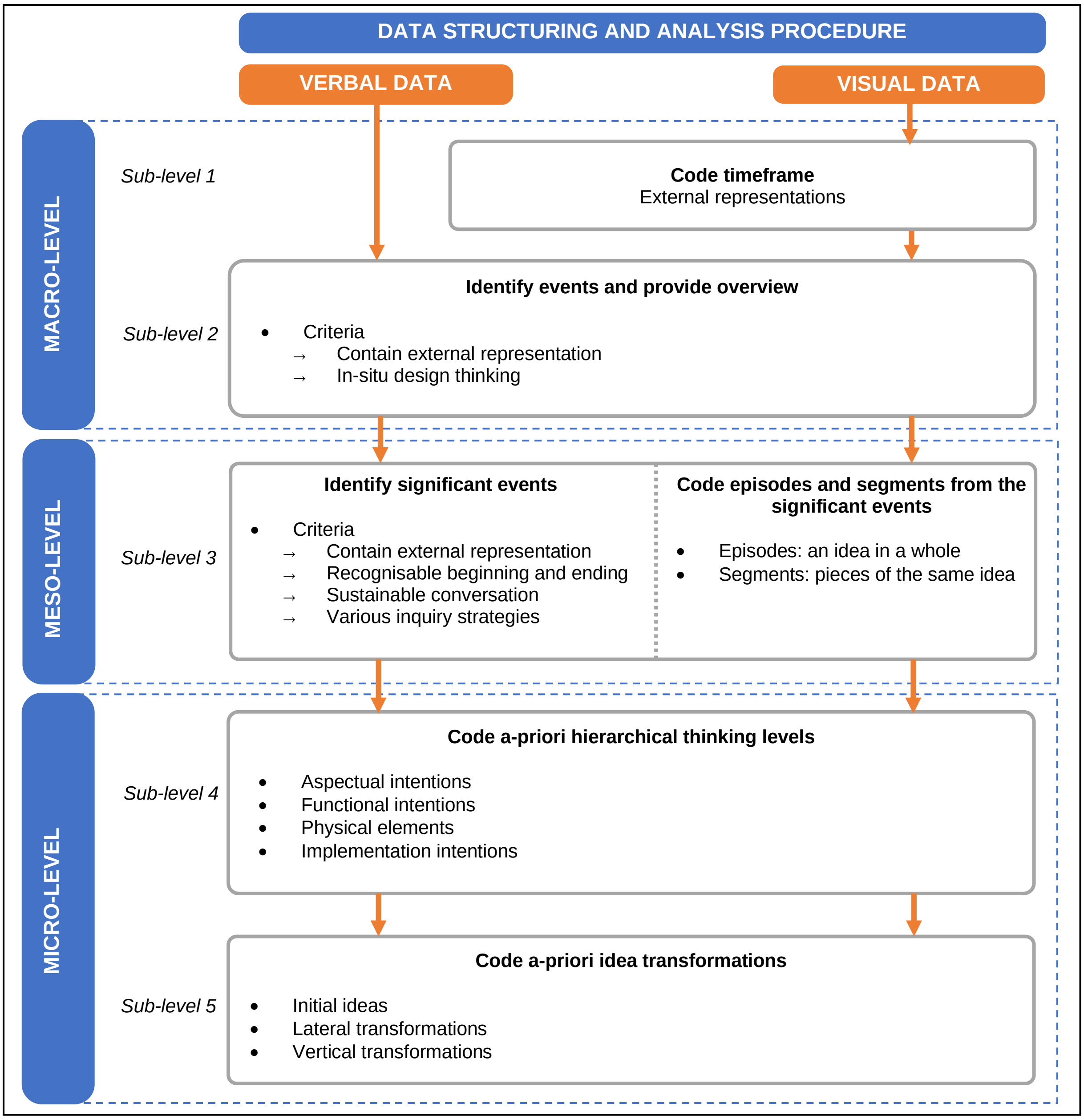


Figure 3.1: Adapted Discourse Analysis methodology from Ash (2007)

The adapted Discourse Analysis methodology from the figure above works in a top-down manner. Focusing on analysing verbal and visual data, it starts with the macro-level analysis containing sub-levels one and two, which is followed by the meso-level analysis containing sub-level three. The data structuring and analysis procedure ends with the micro-level analysis, containing sub-levels four and five. I will now discuss the sub-levels in detail.

Sub-level 1: Code timeframe

Sub-level one entailed coding the time duration of all visual data, which comprised the participants' physical external representations that they made during the completion of the given design task. Coding the time frame seemed to be necessitated in in-vivo methodology (Dunbar, 2001). I considered the participants' physical external representations to encompass the written text, sketches and 3D models that they made during their design processes. I manually coded the timeframe and the relevant participant responsible for making the representation on the back of the photographs of the physical external representations before I transferred the data to Microsoft Excel. Coding the time duration of the physical external representations provided me with quantitative temporal data.

Sub-level 2: Identify events and provide an overview

Sub-level two entailed identifying events and providing an overview of these events. Since the content of designers' thoughts are embedded in their physical external representations (Babapour, 2016; Visser, 2006), I considered participants' coded physical external representations as events. However, the events had to include the participants' in-situ design thinking. After identifying the events, I logically and manually provided an overview for the events through the use of Microsoft Excel, as shown in Figure 3.2.

Timeframe | External representation | Overview

Time	Participant	Stage	External representation	Overview
0:55:39 - 0:58:49	T1_P2	Stage 2	Sketch 1A	**Die forming (female)** Thinking of a male and female mold for die forming the foil into a pod. Speaking about pressing the male and female into one another, which will give the shape of the pod.
0:56:14 - 0:57:39	T1_P2	Stage 2	Sketch 1B	**Die forming (male)** Thinking of a male and female mold for die forming the foil into a pod. Speaking about pressing the male and female into one another, which will give the shape of the pod.
1:00:18 - 1:00:42	T1_P2	Stage 2	Sketch 2A	**Forming gel for female mold** Thinking of forming (rubber) gel as the one side of the mold. Thinking of making the female from the forming gel. T1_P1 disagrees and says that using aluminium will be much better and will last longer. He also mentions that they can 3D prit it out of plastic. However, T1_P2 mentions that he wants to use it to compress, by using the one side to push the blank piece of foil around rather than through a hole.

Figure 3.2: Sub-level two data structuring and analysis

As seen in Figure 3.2 above, I listed the events from the earliest to the latest timeframe with its relevant physical external representation and participant responsible for making it. Thereafter, I watched the video recordings of each listed event and provided an overview thereof. The macro-level analysis was concluded after all overviews were recorded; this was followed by a meso-level analysis.

Sub-level 3: Identify significant events and then code episodes and segments from the significant events

Sub-level three entailed identifying significant events for micro-level analysis. This meant that I had to sift through the listed events and select the ones significant for further analysis. According to Ash (2007), these events have to meet certain criteria to be considered, which are events with (a) recognisable beginnings and endings, (b) sustained conversation, and (c) various inquiry strategies such as questioning, inferring, and predicting. Following the criteria, I watched the video recordings, manually selecting significant events from the Microsoft Excel list made in sub-level two. After identifying the significant events, I coded episodes and segments. I considered episodes as segments put together to make a whole design idea, whereas segments are parts of a whole idea. I manually coded episodes and segments by renaming the selected significant events from the events list, keeping the same format. I thereafter uploaded the video recordings to ATLAS.ti and manually marked the episodes and segments on the video recordings, as shown in Figure 3.3.

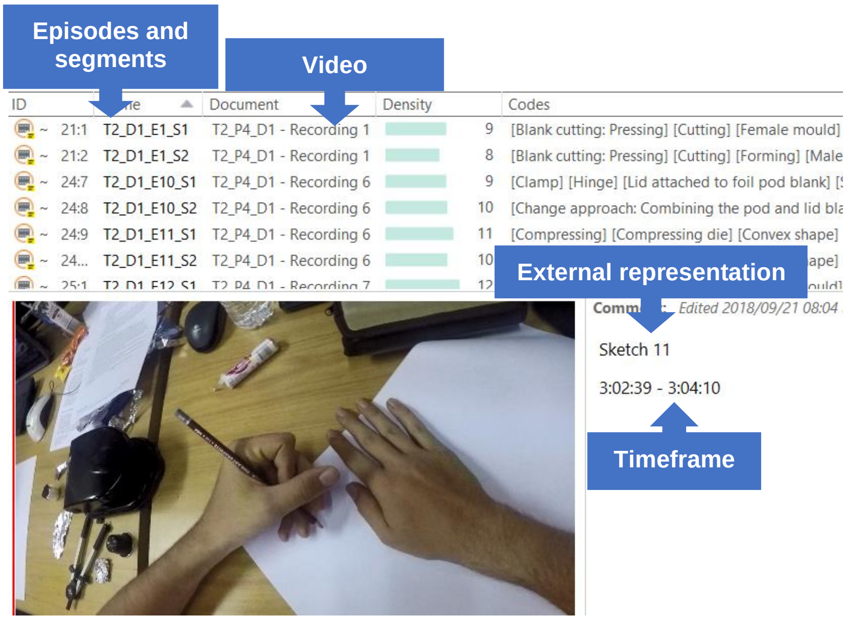


Figure 3.3: Sub-level three data structuring and analysis

As seen in Figure 3.3 above, I coded episodes and segments by marking it on the video recordings. The code that I used was T(n)_D(n)_E(n)_S(n) were T is team, D is the day of the design project, E is the number episode, and S is the number segment in an episode. In each code, I also stated which physical external representation was made and the time duration of the segment. The meso-level analysis was concluded after the episodes and segments were coded, which was followed by micro-level analysis.

Sub-level 4: Code *a-priori* hierarchical thinking levels

Sub-level four entailed coding the hierarchical thinking *a-priori* theoretical constructs consisting of four independent levels, namely, aspectual intentions, functional intentions, physical elements, and implementation intentions. I firstly coded data on aspectual intentions in terms of the things the participants thought were important to aim for in a solution during the preliminary designing, as shown in Table 3.2.

Table 3.2: Identification and coding of aspectual intentions

Aspectual intentions	Description	Example indicators
Aesthetic aspect	Harmony that brings delight to humanity.	*Colour, effect of light and sound.*
Analytical aspect	Conceptualising if something is meaningful.	*Distinction, set apart and classify.*
Biotic aspect	Live functions that act as organisms in an environment.	*Cell, tissue, organism, digestion, reproduction, growth, age and health.*
Economic aspect	The frugal use of resources.	*Business, budgets, money, storing, distributing, recycling, sparing.*
Ethical aspect	Wellbeing and safety.	*Generosity, hospitality, voluntary, vulnerability, sacrifice and renouncement.*
Formative aspect	The deliberate shaping of things.	*Forming, designing, sealing, compressing, constructing, determining and folding.*
Juridical aspect	Appropriateness referring to the responsibility of enforcement, law and policy.	*Groups, roles, cultures, readers, authors, ideas, animals and habits.*
Kinematic aspect	The ongoing and continuous movement of things.	*Morphing, expanding, contracting, rotating, rolling, path and speed.*
Lingual aspect	The expression, recording and interpretation of an artefact.	*Speak, write, hear, read, signal, mark, record, express, understand and quote.*
Physical aspect	Forces, energy and matter of an artefact.	*Material, substance, friction, pressure, heat, power and chemical activity.*
Pistic aspect	Vision that motivates commitment, leading to certainty and belief.	*Dignifying, aspiring, trusting and celebration.*
Quantitative aspect	Numerical amounts and order of quantity.	*One, several, more, less, average, fraction, ratio, tolerance and amount.*
Sensitive aspect	Interactive engagement with the world.	*Hear, see, touch, smell, taste, memory and perception.*
Social aspect	Submerging individuality in social interaction.	*Association, agreement, authority and relationships.*
Spatial aspect	Continuous extension of the surrounding space.	*Shape, position, size, dimension, area, space, overlap and texture.*

Table 3.2 shows the identification and coding of aspectual intentions, which included 15 different aspects (as discussed in Section 2.6). From the 15 aspects, I had to identify which ones the participants considered that provided meaning to the way in which they generated, selected and transformed their ideas while making physical external representations. Secondly, I identified and coded the data on functional intentions in terms of functional questions or statements made by the participants, as shown in Table 3.3.

Table 3.3: Identification and coding of functional intentions

Functional intentions	Description	Example indicators
Functional questions	Questions that refer to an envisaged artefact's expected behaviour in order to derive functional requirements.	*What is the machine supposed to do?* *How will it be able to move?* *How will it be used?*
Functional statements	Statements referring to re-conceptualised functions allowing an envisaged artefact's expected behaviour.	*The machine needs to form coffee pods.* *This will move in a circular motion.* *The machine operates by using hands.*

Table 3.3 shows the identification and coding of functional intentions by looking at the functional questions or statements posed by the participants. Functional questions are typically made when the participants attempted to derive functional requirements from the ill-structured design task where functional statements typically answered their functional questions. Thirdly, I identified and coded data on physical elements in terms of participants' statements on physicality, as shown in Figure 3.4.

Table 3.4: Identification and coding of physical elements

Physical elements	Description	Example indicators
Statements about physicality	Statements referring to geometrical descriptions and the physical makeup of an envisaged artefact, which includes objects, components and lower order properties.	*Handle, shaft, wheel, clamp, pin, edges, flanges, grooves, shape, size, colour, material and texture.*

Table 3.4 shows the identification and coding of physical elements by looking at the participants' statements concerning the physical geometrical structure of their envisaged artefact (Kroes, 2006). Lastly, I identified and coded data demonstrating implementation intentions in terms of the participants' decisions on the fit between an intended function and a physical structure, as shown in Table 3.5.

Table 3.5: Identification and coding of implementation intentions

Implementation intentions	Description	Example indicators
Decisions on functionality and physicality	Statements indicating how the physical nature of an envisaged artefact influences the implementation of intended functions to achieve a desired behaviour.	• *Rounded edges are needed to prevent tearing the foil when being pressed.* • *A concave shape-like press will prevent contents from spilling.*

Table 3.5 shows the identification and coding of implementation intentions by looking at the participants' decisions, indicating their commitment to the fit between particular functional intentions with physical elements. These decisions were observed through the participants' verbal utterances while they were making physical external representations (Haupt, 2018). I manually coded the hierarchical thinking levels on the marked segments through ATLAS.ti. After coding the hierarchical levels, I exported the data to Microsoft Excel in which I could calculate the number of occurrence the codes took place individually, as well as calculating the number of occurrences where codes linked with other codes.

Sub-level 5: Code a-priori idea transformations

Sub-level five entailed identifying and coding the participants' transformation of ideas as *a-priori* theoretical constructs, which included their initial ideas and the lateral and vertical transformation thereof, as shown in Table 3.6.

Table 3.6: Identification and coding of idea transformations

Idea transformation	Description
Initial idea	Initial ideas are originally generated ideas or new generated ideas that are completely different from the original ideas but within one of the same stages in which the designed artefact had to perform.
Lateral transformation	Lateral transformation is when participants transform from one idea to a slightly different alternative idea.
Vertical transformation	Vertical transformation is when participants transform from one idea to a more detailed version of that same idea.

Table 3.6 shows the identification and coding of the participants' initial ideas and lateral and vertical transformations. I identified the moment-to-moment transformations that occurred between the segments of each teams' episodes. Before coding the transformations, I differentiated the segments between the different stages in which the designed artefact had to perform, namely, Stages X, Stage Y and Stage Z (as discussed in Section 3.6.2). In order for me to correctly code the segments, I used an adapted classification scheme from Kato, Okada, and Izu (2018), as illustrated in Figure 3.4.

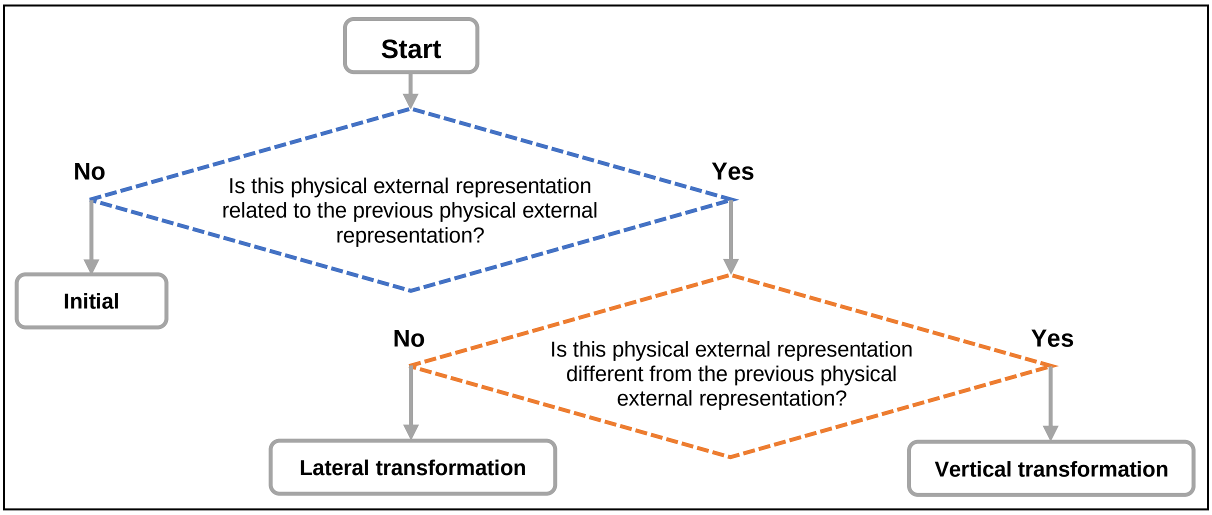


Figure 3.4: Sub-level five: data structuring and analysis, adapted from Kato et al. (2018)

Figure 3.4 shows the classification scheme that I adapted to accurately code the teams of participants' idea transformations. I considered each first segment of an episode as an initial idea, which then underwent transformation. I manually coded the transformations either laterally or vertically on ATLAS.ti. Thereafter, I created a network map using one of ATLAS.ti.'s various tools to demonstrate when initial ideas were generated from the different stages, as well as how the initial ideas were laterally and vertically transformed. An example of the coding is illustrated in Figure 3.5.

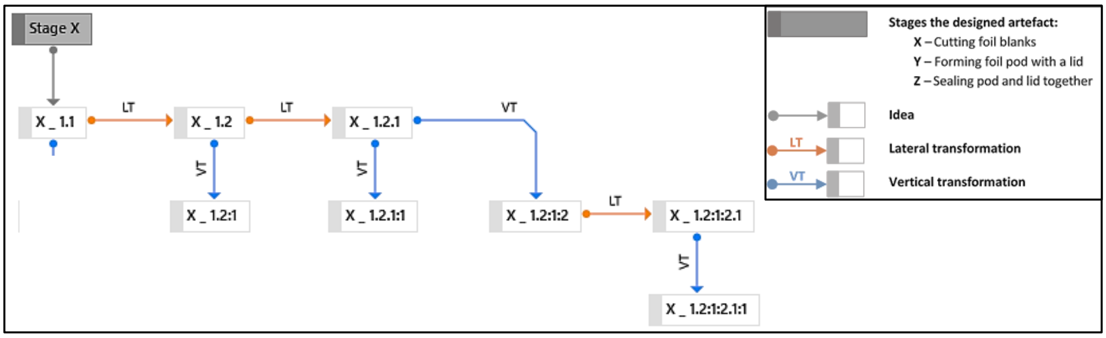


Figure 3.5: Sub-level five: data structuring and analysis

Figure 3.5 provides an example of how I coded the participants' idea transformations using various colours, punctuation marks, lettering and numbering. The stage in which the participants ideas were embedded is indicated by a dark grey box and segments indicated by a light grey box. Lateral transformations are indicated by a full stop (.) and orange coloured arrows pointing horizontally. Vertical transformations are indicated with a colon (:) and blue coloured arrows pointing vertically. In the example, it falls within Stage X, consisting of one episode and nine segments. The episode starts with an initial idea (X_1.1) and contains a lateral transformation (X_1.2). The lateral transformation (X_1.2) also contains a lateral (X_1.2.1) and vertical (X_1.2:1) transformation. The lateral transformation (X_1.2.1) contains two vertical transformations (X_1.2.1:1 and X_1.2.1:2). The second vertical transformation (X_1.2.1:2) contains a lateral transformation (X_1.2.1:2.1), which is then vertically transformed (X_1.2.1:2.1:1). After the coding process, I used ATLAS.ti's network function to visually represent the participants' idea transformation structure for interpretation. The micro-level analysis was concluded after coding the idea transformations.

3.7.2 Data interpretation

Data interpretation was driven by the assumption that novice designers' thinking is characterised by a hierarchical system with nested relationships represented in their ideas transformation. The application of this assumption to the interpretation of data meant that I had to identify *a-priori* theoretical constructs that involve the aspectual intentions at the top of the hierarchy, as demonstrated in Figure 2.1. The data for hierarchical thinking could only be interpreted where verbal utterances and visual externalisations of aspectual intention statements occurred. Aspectual intentions had to form the essence of the participants' drive to find a solution to the given ill-defined design task, which therefore implies that aspectual intentions had to precede functional intentions, physical elements and implementation intentions. In the following step of interpreting the data, I had to search for tangible evidence of the participants linking physical elements with functional intentions, by implication, meeting abstract aspectual intentions. This meant that I had to look for descriptions concerning the artefacts' physical makeup and how this linked with their intended function. Thereafter, I had to interpret the participants' implementation intention found at the bottom of the hierarchy. This meant that I had to look for tangible evidence that represented the participants' confidence about what they perceived as the most likely physical elements to fit the abstract aspectual and functional intentions. Lastly, I had to identify idea transformation *a-priori* theoretical constructs, which involved coding the participants' initial design ideas and their laterally and vertically transformed ideas.

This meant that I had to look for tangible evidence of visual change in the participants' physical external representations, guided by their verbal utterances containing hierarchical intentions.

3.8 QUALITY ASSURANCE

Ensuring valid and reliable data generation, analysis and interpretation procedures for this study, quality assurance measures for case study research designs were followed (Yin, 2014). This study utilised an in-vivo methodology which implied the integration of qualitative and quantitative quality assurance measures to generate trustworthy, valid and reliable findings.

3.8.1 Qualitative measures: Trustworthiness

The notion of trustworthiness in qualitative research addresses research naturalistically by placing emphasis on honesty, depth and richness of the captured data provided by the participants (Cohen et al., 2018; Shenton, 2004). With the purpose of ensuring trustworthiness, I subscribed to four measures of trustworthiness (Lincoln & Guba, 1985), namely credibility, transferability, confirmability and dependability.

Credibility, as described by Lincoln and Guba (1985), relates to the confidence that is being placed in the truth of the findings in this study. This implied that I approached the credibility of this study by ensuring that there was compatibility between the original data the participants generated and the interpretation thereof. I took three measures to ensure the credibility of this study. Firstly, I enhanced the credibility by persistently engaging in observations of verbal utterances captured by the video recordings during data analysis. The credibility of the interpretations that I made about the hierarchical thinking process and idea transformation of the participants was directly dependant on meticulous re-examination of verbal utterances, while constantly testing interpretations made by staying close to the conceptual framework of this study. Secondly, capturing the participants' design processes on video recordings allowed me to repeatedly watch these recordings to determine the context of each of the participants' utterances. I was therefore able to credibly analyse the verbal data in the context of their occurrence since the video recordings not only provided the participants' verbal data, but also showed what they looked at and what physical external representations they were busy making while speaking. Thirdly, I made use of triangulation, which allowed me to study data from more than one viewpoint and to reduce the risk of making fortuitous associations (Creswell, 2014). Credibility through triangulation was established by using two pairs of participants, their physical external representations and verbal protocols. I achieved triangulation by observing the differences and similarities between the participants' data and single-team patterns. I was able to collect four types of data, namely, verbal, visual, temporal, and numerical, which was necessitated by my research questions. Therefore, I was able to enrich the findings by describing each team of participants' cognitive actions by cross-referencing between the data types.

Transferability relates to the extent to which results from a study can be transferred to the contexts of other studies (Anney, 2014; Lincoln & Guba, 1985). Ensuring transferability, I considered two measures identified by Lincoln and Guba (1985). The first being the use of purposive sampling techniques, which I applied to my concurrent mixed methods approach to research. Incorporating purposive sampling techniques enabled me to maximise specific information that I could attain from the research context. The second measure was the affordance of thick descriptions. I attempted to organise utterances made by participants according to the conceptual framework of this study. Therefore, I collected sufficient information about the context in which these utterances were made to allow the readers to determine whether transferability had been successful.

Confirmability in this study relates to the extent to which an examiner can confirm or verify whether the interpretations and conclusions reached are unbiased and can be traced back to their sources (Anney, 2014; Bitsch, 2005; Shenton, 2004). I contributed to the confirmability of the findings by providing an audit trail, which consisted of the following:

- Data generation instrument: The design task (Appendix C1).
- Visual data: Physical external representations (Appendix D1).
- Code book and coding procedures (Section 3.7.1 and, Appendix E1 to E2).
- Data reduction and analysis procedures (Appendix E3 to E7).

Dependability relates to the extent to which the findings of a study are consistent and repeatable (Bitsch, 2005; Shenton, 2004). In the case of this study, replicability is not possible. As such, repeating the same research will not generate exactly identical results owing to the dynamic nature of individuals operating in their normal environment (Merriam, 1998). Nevertheless, I strove to provide consistency in comprehensive explanations of the data coverage (Bogdan & Biklen, 1992; Silverman, 2014). In addition, I attempted to enhance dependability by providing a clear audit trail of my data structuring and analysis procedure in order for this research to be repeated and compared.

3.8.2 Quantitative measures: Validity and reliability

In order to ensure quantitative rigour, validity and reliability measures are normally taken. In this study, I subscribed to validity and reliability guidelines to ensure the quality of this study. These guidelines were construct validity, internal validity, face validity, content validity and inter-rater reliability (Drost, 2011; Jackson, 2015).

Construct validity in this study means to identify correct and operational measures for studying concepts (Jackson, 2015; Yin, 2014) and requires rigorous referral to the conceptual framework while making interpretations of the data. Thus, construct validity refers to how well various levels of intentions, functionality, physicality and implementability, covered by the conceptual framework, measured hierarchical thinking amongst two pairs of participants (Dubery, 2015; Maree, 2016). In particular, I studied the assumptions underlying novice designers' hierarchical thinking processes and the transformation of their ideas during each teams' design processes. In this way, I was therefore able to enhance the construct validity by ensuring that the hierarchical thinking levels and transformation of the participants' ideas were continuously linked to the physical external representations made during their design processes. Following an in-vivo methodology allowed me to describe the participants' moment-to-moment interactions with internal and external sources of information, resulting in a description of novice designers' hierarchical thinking processes and their idea transformations. Although I did not have access to the participants' internal information sources, the Extended Design Cognition Theory, combined with the in-vivo methodology, allowed me to assume that their physical external representations were linked to their working memory (Van Someren et al., 1994), and therefore by implication, to their internal sources of information.

Internal validity relates to the identification of causal relationships among variables (Yin, 2014). The causal relationships specific to this study were between the ill-structuredness of the design task (data generation instrument) and the participants' processing of internal and external information sources to structure and solve a problem. Design problems are ill-structured and characteristically large in size, complex and ambiguous (Goel, 1995), and therefore play a significant role during the early phases of the design process of designers. Thus, internal validity was used to test whether the design task given to the participants complied with the requirements of ill-structured problems and were representative of their design experience. To further test the data generation instrument of this study, face validity and content validity were used.

Face validity means to identify the extent to which an instrument 'looks' valid (Drost, 2011; Jackson, 2015). Face validity cannot be tested or measured, I therefore consulted an expert lecturer in the field of design cognition and Industrial Design to agree on the face validity of the design task given to the participants. An expert lecturer from a local university in Pretoria confirmed the ill-structured nature of the design task that the responsible novice design participants' lecturer had prepared for them.

Content validity means to measure the extent to which the data generation instrument is representative of the sample and the behaviour to be measured (Drost, 2011; Jackson, 2015). This implies measuring whether the data generation instrument is representative of the *a-priori* theoretical constructs embedded in the conceptual framework of this study in order to elicit the participants' hierarchical thinking and idea transformation processes. Attempting to ensure content validity, I employed a concurrent in-vivo methodology, which has been acknowledge to produce multiple sources of valid data to investigate cognitive processes (Ormerod & Ball, 2017).

Inter-rater reliability means to measure the consistency of agreement on observations made by the researcher and one or more raters in an assessment (Jackson, 2015). I attempted to enhance reliability by asking an independent rater in the field of design cognition from a local university. The rater had to classify a sample of ten examples of verbal utterances according to the *a-priori* theoretical constructs, and hierarchical thinking levels and idea transformations in accordance with the *a-priori* theoretical constructs from the conceptual framework of this study. The following formula was used to determine the consistency of agreement between the rater and myself (Jackson, 2015, p. 69):

$$\text{Inter-rater reliability} = \frac{\text{Number of agreements}}{\text{Total number of possible agreements}} \times 100$$

$$= \frac{12}{15} \times 100$$

$$= 80\%$$

A review of the rater's classification revealed a small disagreement noted above (80%), which could be attributed to the fact that the hierarchical thinking levels start out as abstract thoughts which incrementally turn into concrete thinking as their ideas transform (Haupt, 2018). Values ranging between 70% and 100% prove acceptable, according to Stemler (2004). Establishing an acceptable agreement between two sets of *a-priori* coded data seemed to have resulted in reliable interpretations.

3.9 ETHICAL CONSIDERATIONS

In order to study the four third-year Industrial Design student participants, I had to seek permission from various authorities, ensuring that the research was conducted in an ethical manner. Firstly, I sought permission to conduct research from the Ethics Committee of the University of Pretoria's Faculty of Education. Secondly, I sought permission from the Ethics Committee of a local university of technology in Gauteng's Faculty of Engineering and Built Environment (Appendix A2). Thirdly, I sought permission from the Head of the Department of Industrial Design studies (Appendix A3). Fourthly, I sought permission from the lecturer in whose classes I video recorded the design task. Finally, informed consent letters were given to the students participating in the study.

During the process of asking for permission, all authorities received letters in which I explained the aims and procedures of the study (Appendix A1 and B1). Additionally, I emphasised the rights of the participants by explaining the following ethical principles in these letters (Cohen et al., 2018; Maree, 2016):

- Informed consent: A letter with full disclosure of my data collection procedure stating the nature, conduct, benefits and risks of the study was attached to the permission letters. The relevant authorities acknowledged their participation in the study by signing the letters before the research commenced.
- Voluntary participation: Students' participation was completely voluntary, and they could withdraw from the research at any time without any negative consequences or prejudice. One of the limitations of this study was that students who did not want to be part of the research could not be removed from the video recording. Fortunately for this study, withdrawal did not take place.
- Safety during participation: It was unlikely that the participants would be harmed, physically or emotionally. However, working with technical tools in the Industrial Design studio, it was anticipated that physical danger might be one of the concerns regarding the health and safety of the participants. The danger would only occur if participants did not follow the necessary health and safety protocols set out by the Industrial Design lecturers while they were working with workshop tools and equipment. In order to safeguard the participants from potential harm that might occur in the studio, I asked the responsible lecturer and health and safety official to supervise and manage normal procedures while the students were working with workshop tools and equipment. Emotionally, the participants might have felt awkward verbalising their thoughts during the design task. To prevent this, I provided the participants with the opportunity to practice their interactions with each other prior to the commencement of the design task while getting used to the head-mounted cameras. Fortunately, none of the participants were physically or emotionally hurt during this study.
- Participants' privacy: The participants were respected by means of confidentiality and anonymity by omitting their real names. I therefore used codes such as T1_P1 to reference their particular cognitive behaviour during the design task in the verbal and visual data.
- Participants' trust: Adopting a non-judgemental attitude towards the participants, and them operating in the naturalistic setting of the Industrial Design studio, promoted a conducive atmosphere that was best for

performance. Therefore, the participants were not subjected to any acts of deception or betrayal in the research procedures or published outcomes.

- Reciprocal benefit: Possible benefits to the participants included a growing self-awareness of their own design process as well as their own reasoning skills in solving design problems. The participants also indirectly made a contribution towards a better understanding of how to improve design education.

All the raw data has been stored in a locked location at the University of Pretoria, as required by the Ethics Committee of the University of Pretoria. All processed data on my personal computer or back-ups were made on external hard drives and cloud storage, which are all password protected. This way, the identities of the participants are protected. I have also included copies of my coding transcripts and the physical external representations made by participants for the external examiner in order to provide a transparent audit trail. The external examiner can, in this way, judge whether this study was conducted in an honest and neutral manner.

3.10 CONCLUSION

Chapter 3 provided a detailed description of the research methodology employed. I started this chapter by explicating the research paradigm and the research approach that I followed. Thereafter, I situated this study as a descriptive case study research design within the bounds of an Industrial Design learning environment. The participating third-year Industrial Design students were discussed, followed by a thick description of their background context and the selected sampling methods. I then discussed the manner in which I utilised an in-vivo methodology to collect verbal, visual and temporal data. I concluded the chapter by describing the data analysis and interpretation procedures, as well as the quality assurance measures and ethical considerations that were adhered to in the planning and implementation of this study. In the following chapter (Chapter 4), I present the findings of this study.

CHAPTER 4: RESULTS AND FINDINGS OF THIS STUDY

4.1 INTRODUCTION

The purpose of Chapter 4 is to report on and discuss the data analysis and findings in addressing the primary research question of this study, which was:

How does novice industrial designers' hierarchical thinking support the development of their idea transformations during the preliminary design phase?

Chapter 4 presents and discusses the salient results of two teams of novice Industrial Design students working in pairs to solve a given ill-structured design problem. In Section 4.2, I provide an overview of the occurrences of various intentions during the preliminary design phase in which I specifically focus on the number of instances of the teams of novice designers' design intentions. This is followed by Section 4.3 where I discuss how the two teams of participating novice designers transformed their design ideas as represented by the physical external representations that they made.

4.2 OCCURRENCES OF VARIOUS INTENTIONS DURING THE PRELIMINARY DESIGN PHASE

The aim of this section is to discuss the hierarchical thinking of two teams of novice designers in terms of various types of intentions, namely, aspectual intentions, functional intentions, physical elements and implementation intentions. I provide an overview of the main trends of links made between various hierarchical intentions during the preliminary design phase. Thereafter, I provide detailed descriptions of my observations of instances of the two teams' hierarchical thinking. I firstly address the number of instances of aspectual intentions (Section 4.2.1). Secondly, I address the links made with functional intentions (Section 4.2.2), and thirdly the links made with physical elements (Section 4.2.3). Lastly, I address the links made with implementation intentions (Section 4.2.4).

4.2.1 Aspectual intentions

During the preliminary design phase, I observed that the ideas of all of the participants from both teams originated from distinct design aspectual intentions. These aspectual intentions seemingly gave meaning and direction to the way in which the participants generated, selected and developed their ideas, as well as how they committed to some ideas and rejected others. Figure 4.1 captures the number of occurrences of the various aspectual intentions that guided the participants' thought processes.

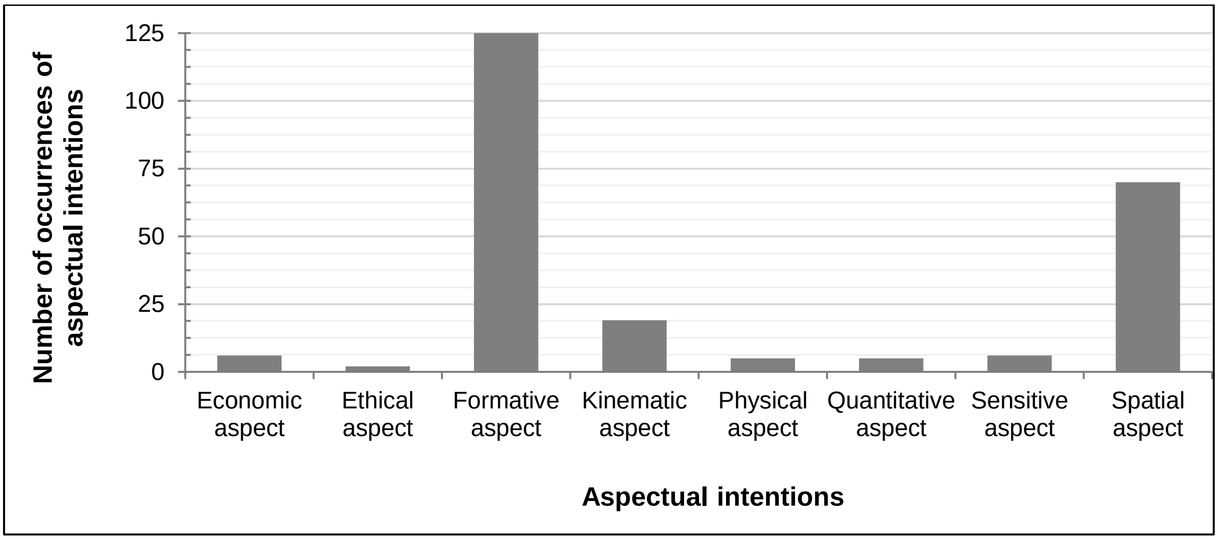


Figure 4.1: Number of occurrences of various aspectual intentions considered during the preliminary design phase

Figure 4.1 shows that the participants only considered eight of the 15 aspectual intentions, according to Dooyeweerd (Basden, 2011), during the preliminary design phase. The participants' attention to the eight aspectual intentions varied throughout their design processes. The aspectual intentions that were mostly considered were the formative aspect with a total of 125 occurrences, which was followed by the spatial aspect with a total of 70 occurrences. The least considered aspectual intentions were the kinematic aspect with a total of 19 occurrences, followed by the economic, ethical, physical, quantitative and sensitive aspects, each with less than 10 occurrences. This means that they intentionally thought about a physical motion (kinematic aspect) that could be applied to a particular shape (spatial aspect) in order to form (formative aspect) the desired shape. This implied that the participants from both teams were thinking of what their envisaged artefact would do and how their envisaged artefact would do it. This finding is supported by previous research as Dubery (2015) has found that the formative aspect and the kinematic aspect are among the most considered aspectual intentions by novice industrial designers.

In order to identify the participants' attention to particular abstract aspectual intentions, I formulated common themes within each aspectual intention to help me in this regard. Table 4.1 illustrates the formulated themes, as well as the number of occurrences of each theme.

Table 4.1: Common themes for identifying aspectual intentions

Aspectual intentions	Themes	Description	Occ
Economic aspect	Cost effectiveness	Cost effectiveness of manufacturing the final product	4
	Recyclability	Reusing some elements of the product created from the final product	2
Ethical aspect	Safety	Considering the safety of the user	2
Formative aspect	Clamping	Holding something tightly in-place	7
	Compressing	Shaping something by applying force	17
	Cutting	Shaping something by removing something by making an incision	29
	Folding	Shaping something by bending over itself	7
	Forming	Shaping something by bringing parts together	29
	Sealing	Shaping something by preventing something escaping	36
Kinematic aspect	Contracting	Decreases in size that cause something to converge or crimp	4
	Expanding	Increasing in size that causes something to break or tear	3
	Rolling	Circular movement in a specific direction moving towards something	3
	Rotating	Circular movement in a specific direction	9
Physical aspect	Material	Matter of which something is made	5
Quantitative aspect	Tolerance	Allowable amount of variation of a dimension	5
Sensitive aspect	Sensory	Physical interaction by using hands	6
Spatial aspect	Shape	Geometrical form of something	60
	Size	Measurement of something relative to the world	8
	Texture	Tactile consistency of a surface	2

Table 4.1 indicates the themes that I formulated to identify aspectual intentions and the occurrence of each theme during the preliminary design phase. I identified 19 common themes, which were categorised according to specific aspectual intentions. The formative aspect comprised the most themes, which included 'clamping' with seven occurrences, 'compressing' with 17 occurrences, 'cutting' with 29 occurrences, 'folding' with seven occurrences, 'forming' with 29 occurrences and 'sealing' with 36 occurrences. This was followed by the spatial aspect, which included 'shape' with 60

occurrences, ‘size’ with eight occurrences and ‘texture’ with two occurrences. The kinematic aspect, which included ‘contracting’ with four occurrences, ‘expanding’ with three occurrences, ‘rolling’ with three occurrences and ‘rotating’ with nine occurrences. The remaining aspectual intentions with their comprising themes occurred seldomly during their thinking processes. As such, the identified themes from the formative, spatial and kinematic aspectual intentions seemed to act as a guiding mechanism for generating and selecting design ideas. The teams of participants, however, considered design aspects differently, which was anticipated because of the dynamic nature of designers operating in their normal environment (Merriam, 1998). Figure 4.2 illustrates the different aspectual intentions that the teams considered.

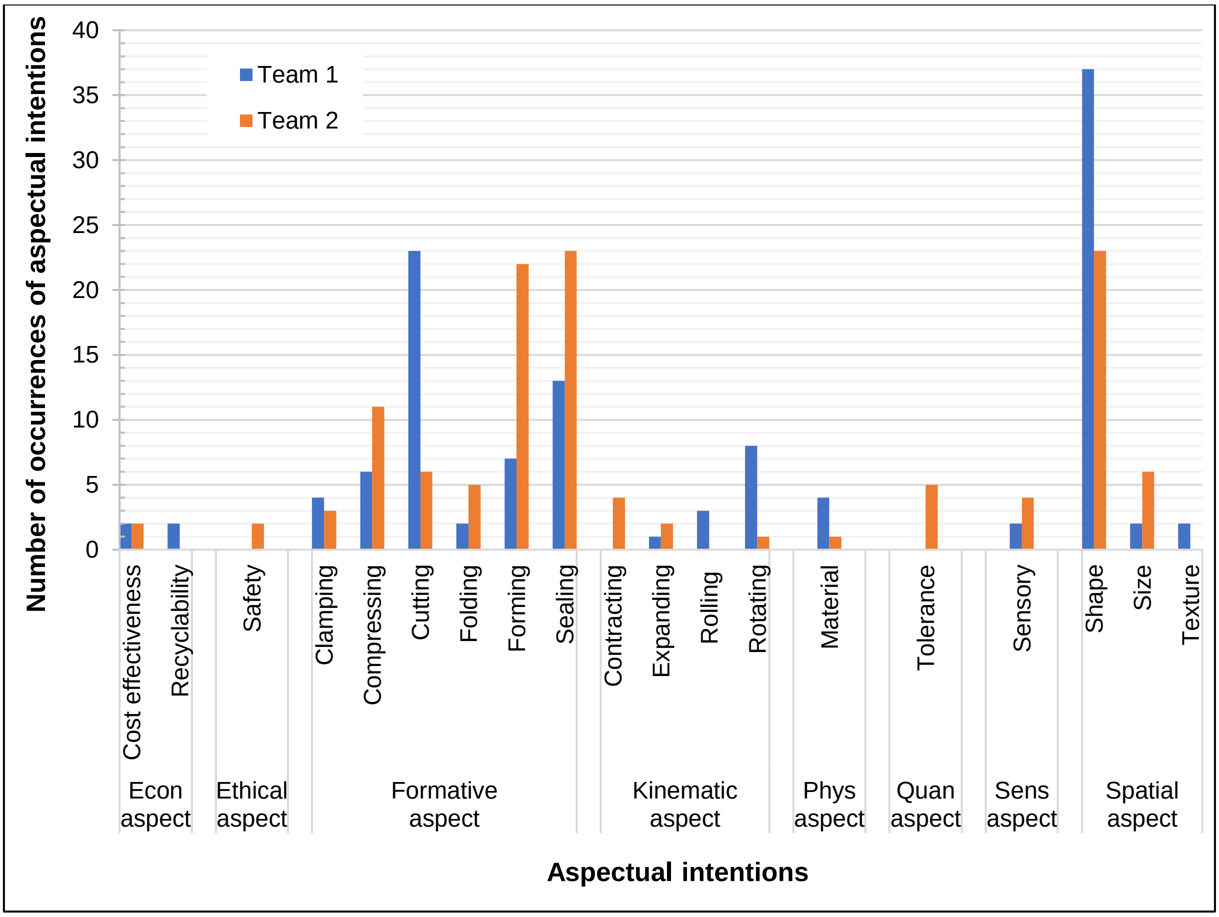


Figure 4.2: Number of occurrences of various aspectual intention considered by the two teams

Figure 4.2 illustrates the number of occurrences of aspectual intentions each team of participants considered during the preliminary design phase. Comparing the data from the two teams in Figure 4.2 shows that the two teams’ attention to the eight identified aspectual intentions differed from one another. On the one hand, the participants from Team 1 only considered six of the eight aspectual intentions in which they gave attention to all themes from the economic, formative, physical, sensitive and spatial aspects, except for the ‘contracting’ theme from the kinematic aspect. The themes that received the most attention among aspectual intentions were ‘shape’ from the spatial aspect with almost 40 occurrences, followed by themes from the formative aspect, namely ‘cutting’ with over 20 occurrences and then ‘sealing’ with over 10 occurrences. The rest of the themes from the six aspectual intentions considered were referred to less than 10 times. This data suggests that the participants from Team 1 concentrated on the formative and spatial aspects, and more specifically the ‘cutting’ and ‘shape’ themes during the preliminary design phase.

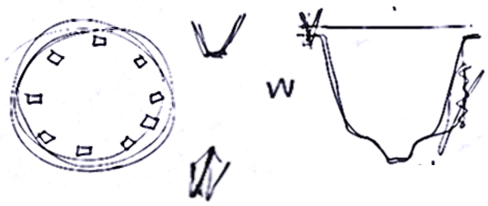
On the other hand, the participants from Team 2 considered all eight aspectual intentions. They gave attention to all themes from the ethical, formative, physical, quantitative and sensitive aspects, except for the ‘rolling’ theme from the kinematic aspect and texture theme from the spatial aspect. The themes that received the most attention among aspectual intentions were ‘shape’ from the spatial aspect and ‘forming’ and ‘sealing’ from the formative aspect, each with more than 20 occurrences, followed by the ‘compressing’ theme from the formative aspect with over 10 occurrences. The rest of the themes from the aspectual intentions considered were referred to less than 10 times. This data seems to suggest that the participants from Team 2 also focused predominantly on the formative and spatial aspects, but more specifically on the ‘forming’, ‘sealing’ and ‘shape’ themes during the preliminary design phase.

Taken together, both teams focused on the formative and spatial design aspects, even though their attention to the eight aspectual intentions differed from one another (Figure 4.2). This might have been due to the information given in the design brief. It is not surprising that the teams were more attentive to the formative and spatial aspects, including ‘cutting’, ‘forming’, ‘sealing’ and ‘shaping’; because these themes correspond with the given design brief instructions. In particular, the three stages that the designed artefact had to perform comprised Stage X – cutting aluminium foil blanks for the pod and lid, Stage Y – forming aluminium foil into pods with a lip, and Stage Z – sealing the lid into the pod once filled with ground coffee. The data therefore seems to suggest that the participants focused on the functionality and physicality of the artefact in design, which is part of the subsequent hierarchical thinking levels (Haupt, 2018), namely, functional intentions and physical elements. Furthermore, this data provides evidence that novice designers, like experts, have the capability to choose and follow particular aspects, and disregard others without rejecting their validity (Haupt, 2018). Their knowledge of particular aspects was typically implied and not specifically explicated. An example of this can be seen in an instance, captured in Excerpt 4.1, where one of the participants from Team 2 explored a design idea applying his knowledge of the formative, spatial and kinematic design aspects to his design idea.

Excerpt 4.1

<u>P4 (1:43:43)</u> – What if we puncture. What if we have an aluminium thing like this right… if you have the two things like this right… What if you punctured like a triangular die in that… or like a thing that looks like this, into that… all around. So, if you have a round thing like this, and then you have a bunch of little square holes, like this right… A bunch of square holes like that, but what it does when it punctures it, it makes little flanges like this at the bottom. So, from the top it will make something like little tabs… Like this, and if you squish it flat, then it will crimp all of those together, sort of like a rivet.

During this instance, demonstrated in Excerpt 4.1, the participant from Team 2 explored a design idea by implying his knowledge about particular design aspects. The participant explored a punch sealing design idea where the punch would puncture through the lip of the aluminium foil pod making a number of flanges made up of foil from both the lip and lid. The participant further explained that the flanges then needed to be pressed flat, allowing the foil from the lip and lid to crimp together in order to seal the coffee pod. The aspectual intentions that the participant considered during this instance comprised the formative, spatial and kinematic design aspects, specifically, the ‘compressing’, ‘sealing’, ‘shape’ and ‘contracting’ aspectual intention themes. As such, evidenced by Photograph 4.1, they explored these aspectual intention themes through making sketches.



P4 exploring an idea of punch sealing the coffee pod by sketching different shapes of punches

Photograph 4.1: P4 considering aspectual intentions while sketching

Illustrated in Photograph 4.1, the participant externally explored the shape of the punch (“*triangular*” and “*square”*) and how the flange from the shape of the punch would allow the lip and lid of the pod to seal (“*squish it flat, then it will crimp all of those together”*). At this point, the participant had not yet specifically stated which shape would be best for making the flanges and how the flanges should be pressed flat. After the sketches were made, the participant thought about testing the design idea physically, which is captured in Excerpt 4.2 and Photograph 4.2.

Excerpt 4.2

<u>P4 (1:47:44)</u> – So, what I’m doing now is mocking up this pressing feature that I was thinking about… It works… It kind of seals. So, I figured out that it does not necessarily work if you press it straight in, it’s like it just pulls out. If you push it through like that, it might work better… Or maybe if you press it in sideways or all around, it would be better.

P4 using a pencil to puncture a piece of folded aluminium foil in order to test an idea for sealing the coffee pod

Photograph 4.2: P4 considering aspectual intentions while physically modelling

Excerpt 4.2 and Photograph 4.2 demonstrate the participant from Team 2 testing his punch sealing design idea. The participant used a pencil as a punch to puncture holes through a folded piece of aluminium foil. After the holes were physically punched into the foil, the participant placed the punctured piece of foil over the table and used his hands to press the flanges flat, causing the foil to crimp together, which sealed the folded sides of the foil together. This exercise was done twice. In the end, the participant still did not specifically state what shape would be best for the punch or how the flanges would be pressed flat sealing the pod, and never again mentioned this during the entire design process. This instance suggests that the participant experienced uncertainty, and in this uncertain state, he only referred to particular aspectual intentions without letting the governing laws of the design aspects influence the design idea (Haupt, 2018). This implies that if the participant allowed the governing laws from the intended design aspects influence his design idea, for example the laws from the kinematic design aspect, such as contracting, expanding, rotating and rolling, he might have investigated what shape would be best for making the flanges; or investigate how the punch should puncture the aluminium foil in order to effectively press the flanges flat, sealing the coffee pod. Furthermore, this instance demonstrates and supports the notion that aspectual intentions are abstract in nature (Goel, 1995; Haupt, 2018). In the following sub-section, I discuss how the participants made links between functional intentions and the preceding aspectual intentions.

4.2.2 Functional intentions

During the preliminary design phase, all of the participants made functional statements about their ideas. These functional statements (intentions) were seemingly triggered by the participants' moment-to-moment attention to specific aspectual intentions. Figure 4.3 captures the number of occurrences where the participants linked functional intentions with aspectual intentions.

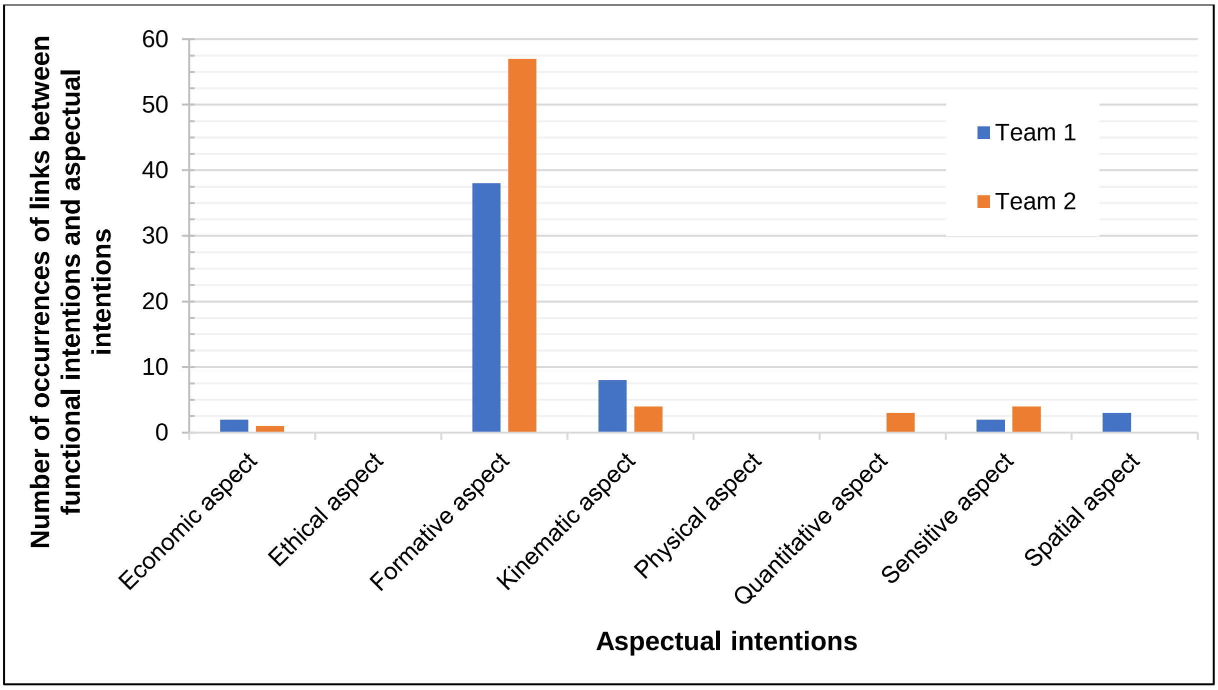


Figure 4.3: Number of occurrences of functional intentions linked with aspectual intention considered by the two teams

The data in Figure 4.3 indicates the number of occurrences of the different teams of participants' functional intentions linked with specific aspectual intentions. Comparing the two teams with one another, the teams thought differently about the functionality of the artefact in design. Team 1, on the one hand, made functional intention links with five of the eight identified aspectual intentions, which included the economic, formative, kinematic, sensitive and spatial design aspects. The majority of functional intention links were made with the formative aspect with over 35 links. The rest of the functional intention links were made with the kinematic aspect with almost 10 links, followed by functional intention links made with the economic, sensitive and spatial aspect, each with less than five links. On the other hand, Team 2 also made functional intention links with five of the eight identified aspectual intentions, which included the economic, formative, kinematic, quantitative, and sensitive design aspects. The majority of functional intention links were made with the formative aspect with over 55 links. The rest of the functional intention links (economic, kinematic, quantitative, and sensitive design aspects) were each with less than five links.

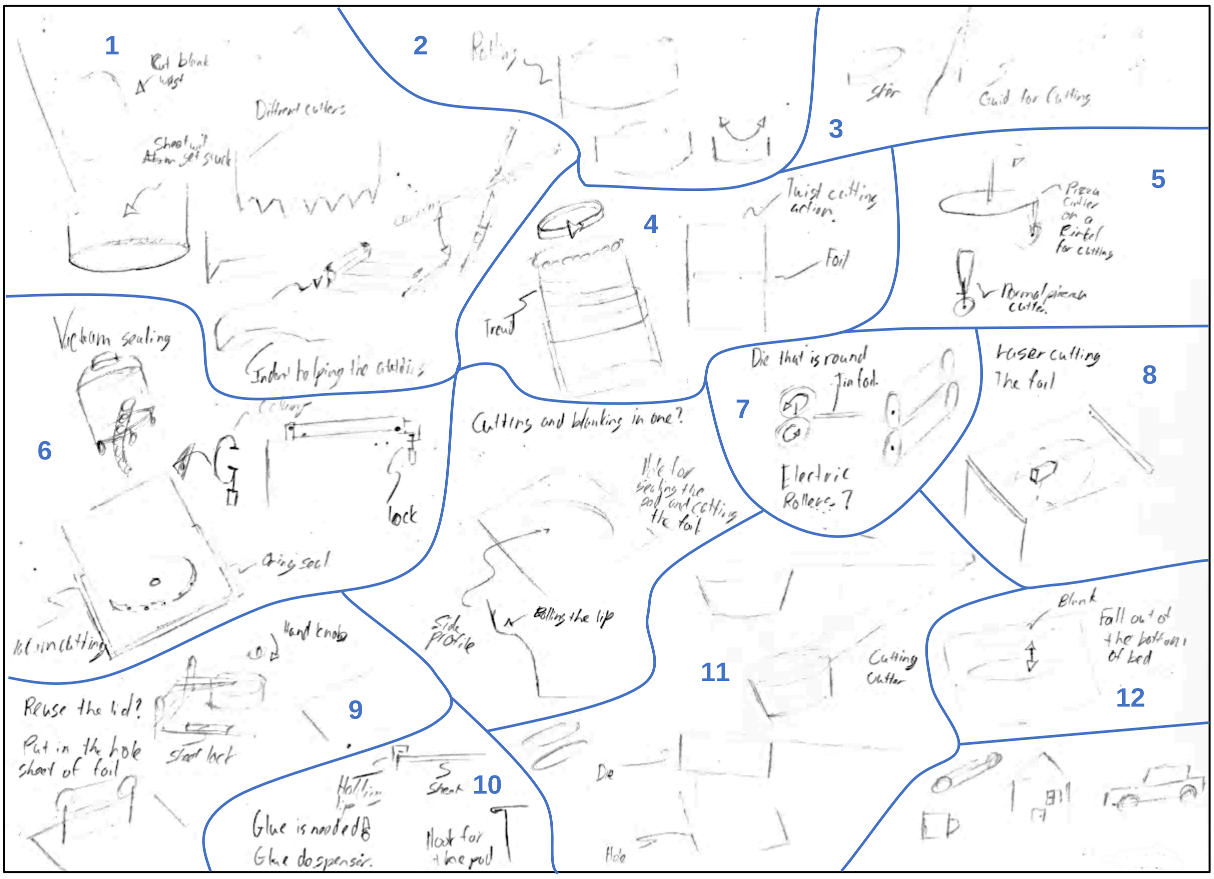
Overall, the data in Figure 4.3 indicates that the majority of the two teams' functional intentions were linked to the formative aspectual intention. This implies that the formative design aspect seemed to be both teams of participants' main driving force behind their functional intentions, which is demonstrated in Table 4.2

Table 4.2: Formative aspectual intentions that lead to functional intentions

Aspectual intentions	Aspectual intention themes	Functional intentions	Overall	
Formative aspect	Clamping	Blank cutting: Clamping shut	6	3
		Sealing: Clamp sealing		3
	Compressing	Pod forming: Compress forming	17	10
		Pod forming: Pressing		3
		Pod forming: Use coffee for compressing		4
	Cutting	Blank cutting: Blade cutting	25	5
		Blank cutting: Clamping shut		1
		Blank cutting: Cutting plate		1
		Blank cutting: Handheld		2
		Blank cutting: Laser cutting		2
		Blank cutting: Pressing		6
		Blank cutting: Punching		1
		Blank cutting: Rolling		2
		Blank cutting: Rotation cutting		1
		Blank cutting: Running rotating blade		1
		Blank cutting: Scoop cutting		2
		Blank cutting: Vacuum cut		1
	Folding	None	0	0
	Forming	Lip forming: Folding foil to make lip	16	1
		Lip forming: Pressing		1
		Pod forming: Pressing		8
		Pod forming: Shear pressing		4
		Pod forming: Slip allowance		1
		Pod forming: Vacuum forming		1
	Sealing	Sealing: Clamp sealing	31	5
		Sealing: Folding lid over pod lip		3
		Sealing: Hand sealing		5
		Sealing: Mechanical sealing		1
		Sealing: Melt pressing		1
		Sealing: Pressing		6
		Sealing: Punch pressing		6
		Sealing: Ring pressing		3
		Sealing: Rolling		1

Table 4.2 illustrates all participants' attention to the formative design aspect, as well as how their formative aspectual intentions lead them to make functional intentions. As such, the participants' attention to the formative design aspect was anticipated since the particular aspect is concerned with the deliberate shaping of things (Basden, 2011). The shaping of things in this sense does not refer to structuring the physicality of the envisaged artefact, but rather to exploring the functions that the envisaged

artefact had to perform in order to shape things. This finding corroborates a study conducted by Dubery (2015), who found that novice designers have the tendency to make more functional intention links with the formative aspectual intention than any other aspectual intentions. However, I observed an unexpected result where one of the participants from Team 1 spent more and longer periods of time attending to functional intentions when he was committed to particular design aspects, which can be seen in Photograph 4.3.



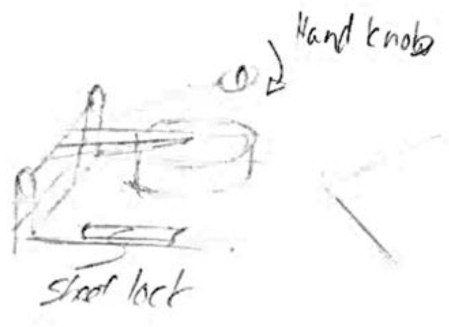
Photograph 4.3: P1 linking functional intentions with aspectual intentions over a period of time

Photograph 4.3 illustrates twelve different instances where functional intention emerged from one of the participants from Team 1's focus on aspectual intentions, namely the formative and kinematic design aspects. These design aspects, in particular, were evidenced in his sketches. These functional intentions primarily linked back to the formative aspectual intention. While sketching, the participant spent much time on exploring various functions that could cut blanks from aluminium foil, which is part of Stage X of the design brief. During this time, the participant explored ideas by connecting vague aspectual intentions, primarily formative aspectual intentions, to functions capable of performing the formative aspectual intention theme of ‘cutting’. As such, instances indicating the linking of formative aspectual intentions with functional intentions are demonstrated in an instance captured in Excerpt 4.3.

Excerpt 4.3

P1 (2:19:58) – Maybe we can have a mechanical way of doing it… Like a rod or something that pushes it down, and it has a hinge or some sort. Something like this, and then it will press down. Something that will look like this, and the sheet will have a little lock or something to keep it in here. Sheet lock… and this knob will go down to have it lock… So, what will happen is that the sheet would have something like this… Making it stronger, this would have a lip to keep it in place, and it will run over here. So, this is a sheet and a holding lip.

During the instance captured in Excerpt 4.3, the participant from Team 1 explored a design idea by linking a functional intention of press cutting with the formative aspectual intention. The participant thought about using something that could press down onto aluminium foil laid flat, cutting it while it was being kept in place. The participant attempted to conceptualise this design idea by means of sketching, as illustrated in Photograph 4.4.



P1 sketching an idea of using something that could press down onto aluminium foil cutting it while being kept in place

Photograph 4.4: P1 linking functional intentions with aspectual intentions while sketching

Photograph 4.4 illustrates how the participant from Team 1 externally conceptualised the design idea by connecting his functional intention of press cutting with the formative design aspect of ‘clamping’, compressing’ and ‘cutting’. During this instance, the participant indicated keeping the aluminium foil in place by 'clamping' the foil with "*a little lock*" allowing the press cutting function to take place; and then 'cutting' the foil blanks by 'compressing' a "*rod or something*" downward.

In another instance, the participant not only linked the formative design aspect with functional intentions, but also to the kinematic design aspect. This instance is captured in Excerpt 4.4.

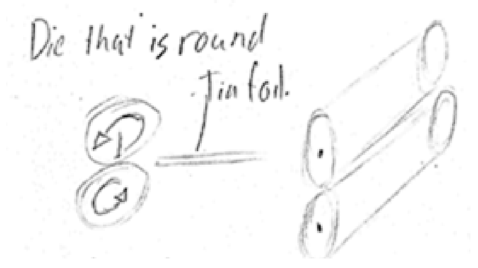
Excerpt 4.4

P1 (2:43:34) – That's not a bad idea, why don't we make it or incorporate it, so when you put in the foil… and it's a long machine, and then you roll it, and the die will cut it, and it will push it forward and then we can seal it. And it's just a longer machine.

P2 (2:43:56) – You cannot press foil like that. It will crimp just like that. You will need a bed to move it.

P1 (2:44:05) – I mean, you just need to have another roller. So, two rollers. It has to have a bottom one to be able to cut. So, it will just move the bottom one forward and then you will have the waste run up with something like that. That could work. Die that is round… So, the rollers would look something like that.

During the instance captured in Excerpt 4.4, the participant from Team 1 explored a design idea again by linking a functional intention of rolling cutting with the formative and kinematic aspectual intentions. The participant thought about using a rolling action applied to something circular in order to cut aluminium foil. The participant attempted to conceptualise this design idea by making sketches, as illustrated in Photograph 4.5.



P1 sketching an idea of cutting aluminium foil using a rolling action applied to something circular

Photograph 4.5: P1 linking functional intentions with aspectual intentions while sketching

Photograph 4.5 illustrates how the participant from Team 1 externally conceptualised the design idea by connecting his functional intention of rolling cutting with the formative and kinematic design aspects, specifically, the formative aspectual intention theme of 'cutting', as well as the kinematic aspectual intention themes of 'rolling' and 'rotating'. During this instance, the participant indicated that the intended function would have a second function with regard to considering the kinematic aspectual intention. He indicated that the 'rolling' action, as the main function, would not only "*roll… and… cut*" aluminium foil blanks, but also act as a 'rotating' mechanism, the second function, to feed ("*push it forward*") foil sheets through the envisaged artefact for 'cutting'. Even though the participant referred more to the kinematic than the formative aspectual intention, the focus was mostly on the formative aspectual intention in order to enable the intended function.

The participant's commitment to the formative design aspect was mainly to derive functions, in this case press cutting and rolling cutting, intended to realise the formative aspectual intentions. This implies that the participant's abstract aspectual thoughts led him to conceptualise the intended functions of press cutting and rolling cutting. These instances suggest that the formative design aspect seemingly guided the way in which the participant made functional intentions while considering other aspectual intentions simultaneously. This implies that the participant attempted to address insufficient and unspecified information from the design brief in order to derive the functional requirements expected to be achieved (Haupt, 2018). The examples from Excerpts 4.3 and 4.4 highlight the participants' tendency to spend more time on making functional statements when focused on a particular aspectual intention. This tendency was also pointed out in studies conducted by Suwa et al. (1998) and Cross (2001a). Furthermore, it is important to mention that in both examples, the participant made references to physical elements, however, it was not the participant's intention to match functionality with physicality at that point in time, but rather to explore functionality as his understanding of the context developed (Goel, 1995). In the following sub-section, I discuss how the participants made links between physical elements and the preceding aspectual and functional intentions.

4.2.3 Physical elements

During the preliminary design phase of problem solving, I observed that the participants from both teams made statements regarding the physicality of their envisaged artefact. These statements are physical elements that relate to the material nature of an artefact, which include statements about the artefact, its components and what properties the artefact may be made up of (Haupt, 2018). Making statements like these allowed the participants to transform their abstract thoughts into a concrete embodiment of aspectual and functional intentions. I observed the teams of participants to not only make physical element link with their functional intentions, but also to make links with aspectual intentions. Figure 4.4 captures the number of occurrences where the teams made physical element links with their prior aspectual and functional intentions.

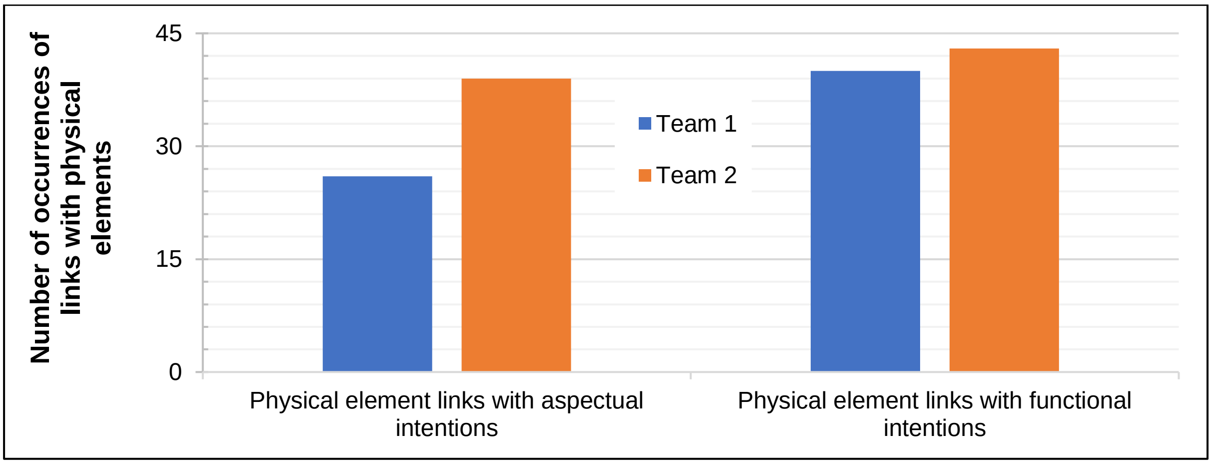


Figure 4.4: Number of occurrences of physical element links with aspectual and functional intentions by the two teams

The results captured in Figure 4.4 indicate both teams' number of occurrences where links were made between physical elements and aspectual and functional intentions. Figure 4.4 shows that both teams of participants thought almost similarly about the physicality of their envisaged artefact. Team 1 made a total of 66 physical element links, where 26 links were made with aspectual intentions and 40 links with functional intentions. Team 2 made a total of 82 physical element links, where 39 links were made with aspectual intentions and 43 links with functional intentions. In total, these results indicate that Team 1 made less physical element links with aspectual and functional intentions than Team 2. A study conducted by Goldschmidt (2013), which investigated the dynamic links made between aspectual and functional intentions (rationale) and with physical elements (embodiment), reports similar results. However, the focus of Goldschmidt's (2013) study was on the design reasoning that designers' engage in based on rationale and embodiment, which is different from this study. I focused on how the links between hierarchical intentions support their idea transformations, and therefore the results of this study should be interpreted with caution. Furthermore, Figure 4.5 captures the number of occurrences where the two teams made physical element links with aspectual intentions.

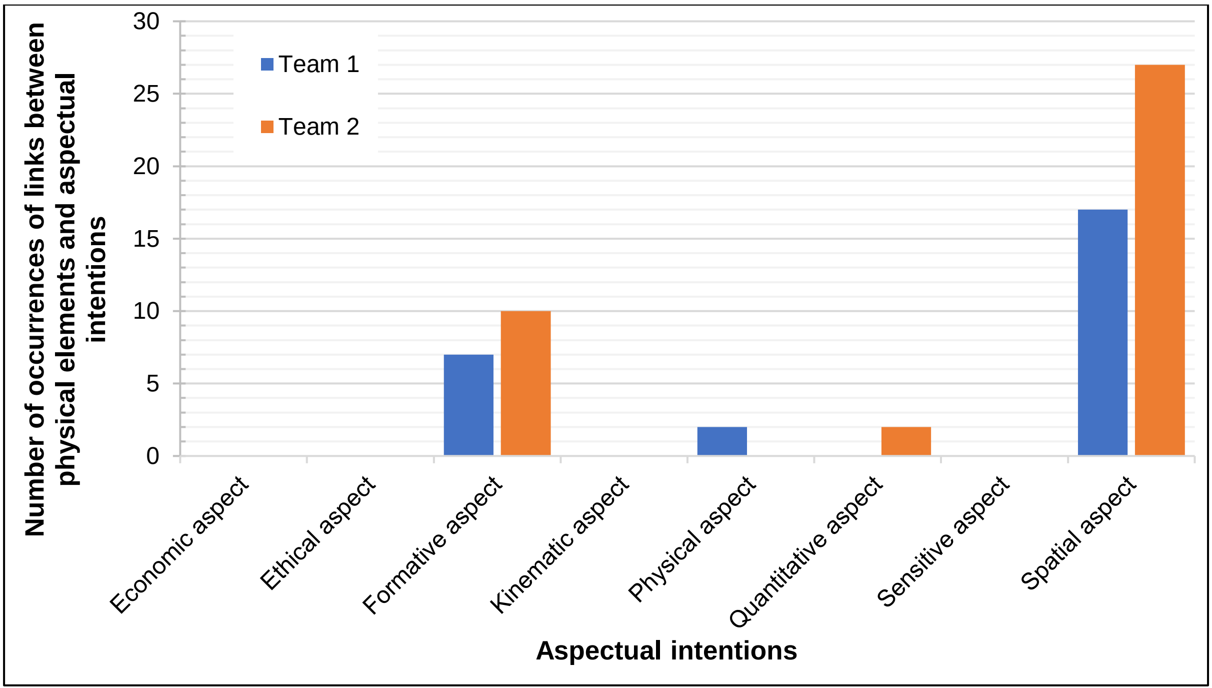


Figure 4.5: Number of occurrences of physical element links with aspectual intentions by the two teams

Figure 4.5 above illustrates the teams of participants' physical element links with aspectual intentions. On the one hand, Team 1 made a total of 26 links in which the spatial aspect was considered the most with 17 links, followed by the formative aspect with seven links, and the physical aspect the least with only two links. On the other hand, Team 2 made a total of 39 links, where the spatial aspect was considered the most with 27 links, followed by the formative aspect with 10 links, and the quantitative aspect the least with only two links.

Overall, the data in Figure 4.5 indicates that the majority of the two teams' physical elements were linked to the spatial and formative aspectual intentions. This implies that the spatial and formative design aspects seemed to be the main driving force behind their links between physical element and aspectual intentions, which is demonstrated in Table 4.3.

Table 4.3: Spatial and formative aspectual intentions that lead to physical elements

Aspectual intentions	Aspectual intention themes	Physical elements	Overall	
Formative aspect	Clamping	None	0	0
	Compressing	None	0	0
	Cutting	None	0	0
	Folding	Folding lid over lip edge	5	2
		Folding lines		1
		Hinge		2
	Forming	Female mould	11	8
		Groove		1
		Male die		2
	Sealing	Air-tight	1	1
Spatial aspect	Shape	Channel	39	2
		Female mould		12
		Handle		2
		Lip rolled over the edge		3
		Male die		7
		Pod shape when sealed		1
		Shape of actual pod (existing artefact)		1
		Taper shape		8
		Tide pod		1
		Triangular die		2
	Size	Forming foil around existing artefact	5	1
		Size of lid blank		2
		Size of the pod blank		2
	Texture	None	0	0

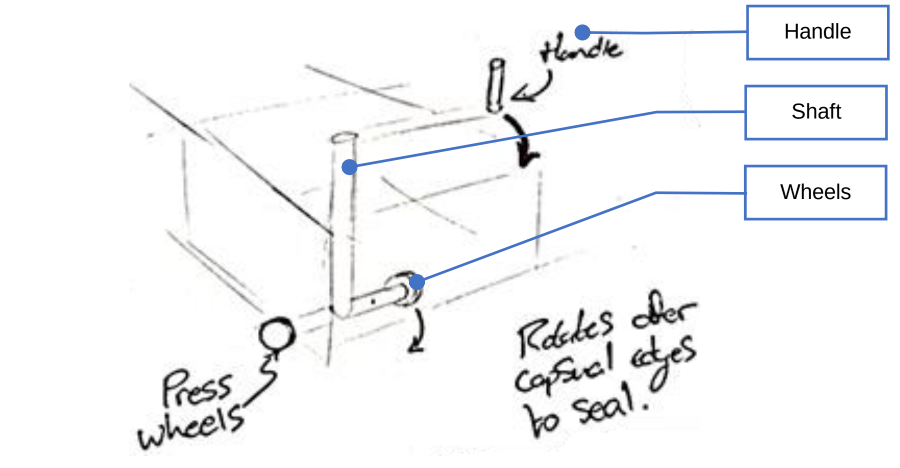
Table 4.3 illustrates all the participants' attention to the spatial and formative design aspects, as well as how their spatial and formative aspectual intentions lead them to make physical elements. An example of this can be seen in an instance captured in Excerpt 4.5.

Excerpt 4.5

*P2 (2:24:48) – So, here you got your **handle**… and then the **shaft**… and then this is coming out, the wheels… on each side. This rotates… this too. A press, so we need a block here.*

*P2 (2:27:15) – A handle… Press **wheels**… Rotates after capsule edges to seal.*

Excerpt 4.5 demonstrates an instance where one of the participants from Team 1 made physical element links with aspectual intentions. The participant thought about using wheels pressing down on the aluminium foil coffee pod, sealing it with a rotating motion. The design idea was evidenced by his sketch illustrated in Photograph 4.6.



P2 sketching an idea of sealing aluminium foil blanks using press wheels

Photograph 4.6: P2 linking physical elements with aspectual intentions while sketching

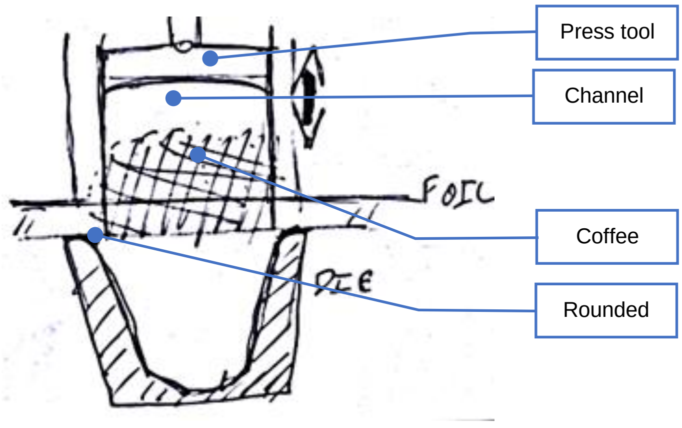
Photograph 4.6 illustrates the participant's links made between physical elements and aspectual intentions. During this instance, the participant proposed a structure consisting of three components, namely, a 'handle', 'shaft' and 'wheels', and then mentioned that these components would rotate. These components, or physical elements, were linked with the kinematic aspectual theme in terms of 'rotating'. Thereafter, the participant stated that in order to press something, a block-like structure is needed, which he placed around the other physical elements. This physical element was linked with the formative and spatial aspects based on the aspectual themes of 'compressing' and 'sealing'. While discussing the physical elements, the participant also made reference to functional behaviour, namely, rotating and pressing. However, it was not the participant's intention to propose a structure to be linked to an intended function, but it was rather an attempt to understand how these physical elements work together in order to propose a function. I interpreted the participants' statements on rotating and pressing as part of aspectual intentions because of the aspectual intention themes I used to identify aspectual intentions, as discussed in

Section 4.2.1. Furthermore, looking at the whole instance, the participant did not explicitly state why the physical elements are used for rotating and pressing, which therefore suggests that the participant's thoughts were more abstract than concrete with little commitment to the design idea. Making physical element links with functional intentions represents the participant's thinking to be more concrete. An example of this can be seen in an instance captured in Excerpt 4.6.

Excerpt 4.6

> P4 (2:10:16) – *When we pile the coffee on, we need a blank. We need a… so, when we pile the coffee, we need the aluminium here, the foil, the die… the die would be like this. So, that's your die right… you have your aluminium foil. So, its foil, die and then you get the* ***coffee*** *grounds here. What we can do to mitigate your situation, is have the* ***coffee*** *grounds… have a thing sort of like that… a* ***channel****. You have a gap here right, so you put the, you clamp. So, this thing moves up and down right… it makes contact with this surface or lifts up. So, in stage one it will make contact with the surface, you will have* ***coffee*** *grounds here, like this, and then you will have your press tool that comes down this* ***channel****. So, you will have your* ***press tool*** *coming down like that, with fairly high tolerance part coming down the shaft, pressing the coffee into the die. This obviously have to be* ***rounded****, so that the foil does not crinkle or tear, and then that is pressed in. Then you lift this up so that you have space here, then you shove your aluminium foil in, then you press this tool here down again.*

Excerpt 4.6 demonstrates an instance where one of the participants from Team 2 made physical element links with functional intentions. The participant thought about compressing coffee grounds through a channel into a female die, filling and forming aluminium foil blanks instantaneously. The design idea was evidenced by his sketch, as illustrated in Photograph 4.7.



P4 sketching an idea of forming aluminium foil blanks by compressing coffee grounds through a channel

Photograph 4.7: P4 linking physical elements with functional intentions while sketching

Photograph 4.7 illustrates an instance where the participant from Team 2 made physical element links with functional intentions. During this instance, the participant was in the process of proposing a structure for forming aluminium foil coffee pods. The proposed structure consisted of a few physical elements, namely, a female die, channel, press tool and rounded edges. The participant explained that a piece of aluminium foil would be placed between the female die and the channel, where coffee grounds would be poured through the channel onto the aluminium foil. The press tool would press down through the channel and compress the coffee grounds in the female die and, by implication, form the aluminium foil pod. The female die should have rounded edges that would prevent the foil from tearing when being compressed. During this instance, the participant linked these physical elements to the functional intention of compress forming, attempting to propose a structure to fit an intended function. Furthermore, the participant's utterances and sketches contained an increased amount of detail, which indicated his growing commitment to the particular design idea.

In summary, the occurrences between physical elements and aspectual and functional intentions together (Figure 4.5) were much more compared to those between functional intentions and aspectual intentions (Figure 4.4), as discussed in Section 4.2.2. This might have been due to the participants attempting to provide their functional intentions with a suitable physical structure, which, by implication, met with their vague aspectual intentions. I further observed that the participants chose to externally develop their ideas in search of an optimum fit between their intended functions and a physical structure suitable for the design requirements. The search included the participants attempting to (a) understand the structure of the coffee pod that the envisaged artefact had to produce; (b) find a suitable structure for the intended function of the envisaged artefact; and (c) find a suitable structure for the envisaged artefact in which the intended function could operate. This might have been due to the participants' continuous attempts to satisfy the need to achieve the dual nature of their envisaged artefact (Kroes & Meijers, 2006), by finding an optimum fit between their suggested physical elements and intended functions. During this search for achieving a dual nature, both teams were observed to increase the amount of detail in their physical external representations once they became committed to selected ideas. Having selective attention to design ideas suggests that the participants' physical external representations played a cognitive role in the increasing amount of detail in their sketches (Babapour, 2016). This suggests that all the participants were becoming more certain to what is expected of them in the design brief (Haupt, 2018). In the following sub-section, I discuss how the participants made links between implementation intentions and the preceding aspectual intentions, functional intentions and physical elements.

4.2.4 Implementation intentions

During the preliminary design phase of problem solving, I observed that all of the participants from both teams incrementally developed their design ideas by making decisions about their functional intentions and physical elements. The articulation of these decisions indicated the participants' intention to implement an intended function or physical structure for their envisaged artefact, demonstrating their commitment to particular functional intentions and physical elements (Haupt, 2018). The distinguishing characteristic of implementation intentions was when the teams referred to an activity, for example, 'you can put the blade on a disk, and it will cut in a circular motion', which is more concrete than the abstract aspectual intention themes identified. Figure 4.6 captures the number of occurrences where the teams of participants made implementation intention links with their functional intentions and physical elements.

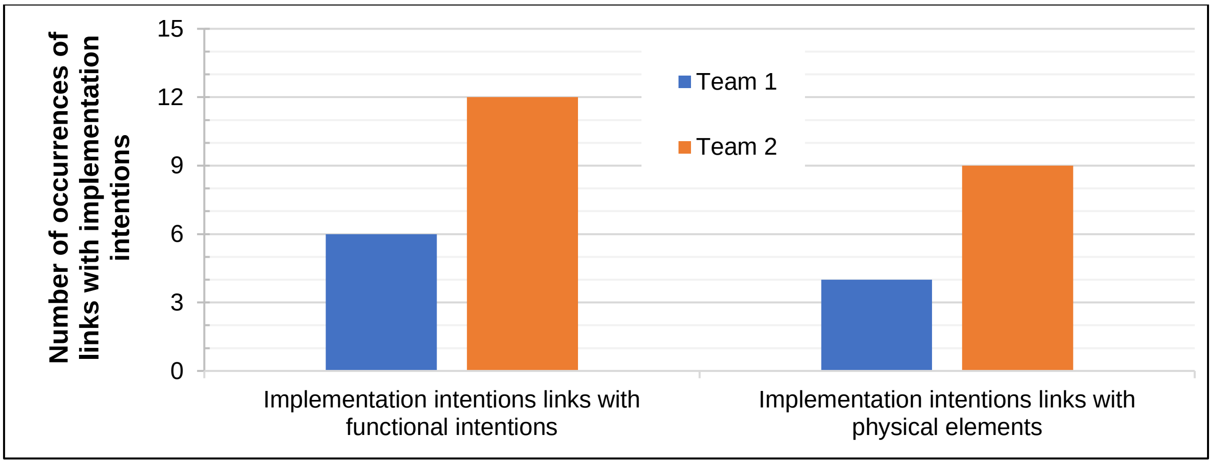


Figure 4.6: Number of occurrences of implementation intention links with functional intentions and the physical element by the two teams

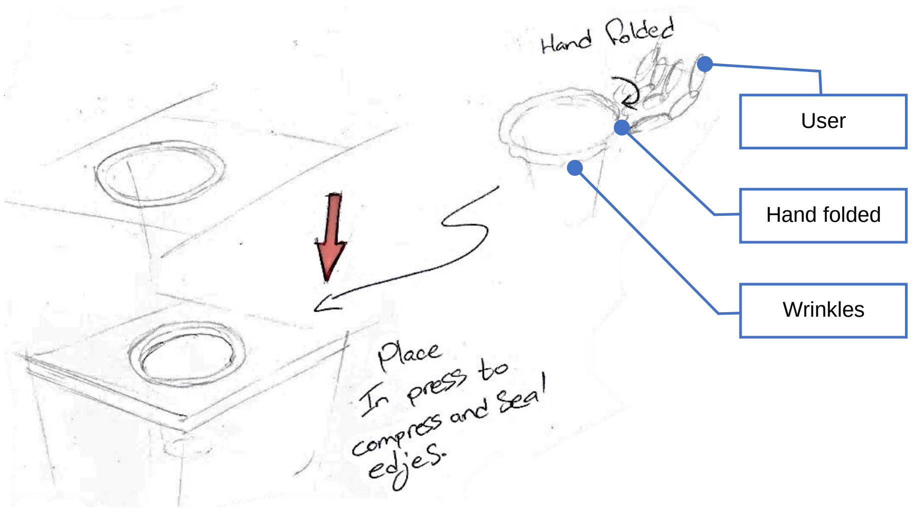
The results captured in Figure 4.6 indicate both teams' number of occurrences where implementation intention links were made with functional intentions and physical elements. No links between implementations intentions and aspectual intentions were observed. Team 1 made a total of 10 links, where six links were made with functional intentions and four links were made with physical elements. Team 1, alternatively, made a total of 21 links, where 12 links were made with functional intentions and nine links were made with physical elements. Comparing the two teams with one another, Team 1 made less links than Team 2. However, both teams were observed to articulate their commitment to particular design ideas once an optimal fit between the intended function and a physical structure was thought to be made. An example of this can be seen in an instance captured in Excerpt 4.7.

Excerpt 4.7

*P2 (1:35:14) – I don't know how to seal it, maybe just use your hand and press… Get the **guy** (user) involved.*

*P2 (1:43:35) – I'm just drawing this thing, it has **wrinkles** all the way around. And then fold it over. **Hand folded**. Place in press to compress and seal edges.*

Excerpt 4.7 demonstrates an instance where one of the participants from Team 1 made implementation intention links with the preceding intentions. The participant stated that the user operating the envisaged artefact had to be physically involved in the sealing of the coffee pod using his or her hands. The design idea indicating this statement was evidenced by the participant's sketch illustrated in Photograph 4.8.



P2 sketching an idea of folding aluminium foil pod lip by hand

Photograph 4.8: P2 linking implementation intentions with preceding intentions while sketching

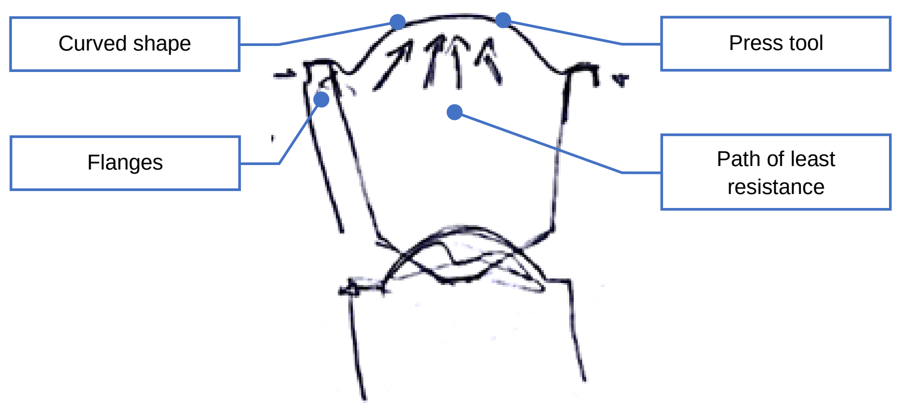
Photograph 4.8 illustrates the instance where the participants from Team 1 made an implementation intention while in the process of suggesting ways to fold the lip of the aluminium foil pod over the pod lid in order to seal the two together. During this instance, the participant suggested that the user ("*guy*") operating the envisaged artefact should be involved in sealing the coffee pods. This meant folding the lip over the lid by hand and then compress sealing the aluminium foil pod after being placed back in the forming die. In this instance, the participant made an implementation intention link with a functional intention. The participant struggled to suggest a suitable physical structure for the intended function of folding the lip over the lid, and therefore made an implementation intention stating that the user should fold the lip by hand. The participant's commitment to the implementation intention might have been due to the requirements of the design brief, which includes the artefact being hand operable.

In another instance, one of the participants from Team 2 made an implementation intention link with physical elements, which is captured in Excerpt 4.8.

Excerpt 4.8

*P4 (2:06:36) – What if we made the **press tool**, like that, and then like that and that. So, your coffee is inclined to go into this space, as supposed to go off there. So, you have your press tool, sort of be like this, for the top, for when it goes on top of the coffee, you have if be shaped like this. And then you have your bottom come in like this… sorry, like this. Just drawing it roughly like that. So, your coffee doesn't want to go out there, it wants to go up, because it will always follow the **path of least resistance**. We've streamlined it to go up here… so, this will go all the up to this, into this part. And this can shove the **flanges**, so that can do the job of that. And then we can put a piece of tin foil over it and then just crimp it.*

Excerpt 4.8 demonstrates an instance where one of the participants from Team 2 made an implementation intention link with physical elements. The participant specifically stated how the shape of the pressing tool would look in order to compress coffee in an aluminium foil pod. The design idea indicating this main goal was evidenced by the participant's sketch illustrated in Photograph 4.9.



P4 sketching an idea of compressing coffee in aluminium foil pod

Photograph 4.9: P4 linking implementation intentions with physical elements while sketching

Photograph 4.9 illustrates an instance where the participants from Team 2 made an implementation intention with physical elements while in the process of defining the shape of the pressing tool so that coffee grounds would be compressed effectively inside an aluminium foil pod. During this instance, the participant suggested that the pressing tool shape should be curved and that the press tool should extend over the lip of the forming die. The participant explained that using a curved shape that covers the entire forming die would minimise coffee grounds escaping on all sides when being compressed. In this instance, the participant made an implementation intention link with physical elements in order to fit an intended function. The participant struggled to suggest a suitable physical structure for the intended function, however, suggesting a curve shaped pressing tool covering the forming die would allow coffee grounds to be compressed without hassle. The participant's commitment to this implementation intention indicated a high level of certainty, which was observed to be propagated in their following design ideas. Similar findings were recorded in a study conducted by Brandstätter, Heimbeck, Malzacher, and Frese (2003), which found that designers' implementation intentions, their commitment to particular functional intentions and physical elements, typically directs the way in which they further incrementally develop their design ideas. This implies that designers' implementation intentions are typically seen further on in their design processes when they either generate new design ideas or transform their existing design ideas.

In summary, the results for implementation intention links with functional intentions and physical elements together are much less compared to the links made between the preceding intentions discussed in Section 4.2.2 and 4.2.3. This was expected since implementation intentions served as a saturation point (Haupt, 2018) whilst the participants were becoming committed by incrementally developing their design ideas (Goel, 1995). The participants from both teams were observed to propagate their commitments to intended functions and physical elements in their following design ideas (Brandstätter et al., 2003).

4.3 IDEA TRANSFORMATIONS DURING THE PRELIMINARY DESIGN PHASE

The aim of this section is to present how the ideas from both teams transformed during the preliminary design phase. The way in which designers transform their design ideas is done through either lateral transformation, i.e. moving from one idea to a slightly or completely different alternative idea, or vertical transformation, i.e. moving from one idea to a more detailed version of that same idea (Goel, 1995; Haupt, 2018). The transformation of ideas in an extended cognition context occurred through participants' external perceptual stimulation, which emerged from their spoken and written words, as well as their hand-drawn sketches. During the preliminary design phase, I observed that all the participants generated initial ideas and then transformed these ideas either laterally or vertically. An overview of the initial, transformed and total number of ideas generated from the teams is depicted in Table 4.4.

Table 4.4: Overview of the initial, transformed and total number of generated design ideas

Team	Initial ideas	Laterally transformed ideas	Vertically transformed ideas	Total ideas
Team 1	26	12	27	65
Team 2	23	12	21	56

Table 4.4 captures the teams of participants' initial, transformed and total number of generated ideas and indicates that Team 1 generated less ideas than Team 2 in the time given. A common trend seems to exist where both teams generated more initial and vertically transformed ideas than laterally transformed ideas, which is consistent with findings from a study conducted by Song and Agogino (2004). This might be due to the large amount of functional intention links made with aspectual intentions and physical element links made with aspectual and functional intentions, as discussed in Sections 4.2.2 and 4.2.3.

Further analysis also revealed that the two teams focused differently on the prescribed stages in which the designed artefact had to perform, as specified by the design brief. These stages can also be seen as part of the formative aspectual intention, as discussed in Section 4.2.1. Both teams were observed to focus individually on the different stages. However, they were also observed to cooperatively focus (in their teams) on some stages simultaneously. This resulted in the teams developing combined stages, namely Stage XY: Blank cutting and pod forming and Stage XZ: blank cutting and sealing. Figure 4.7 presents the two teams' number of foci on the different stages in terms of their initial, laterally transformed and vertically transformed ideas.

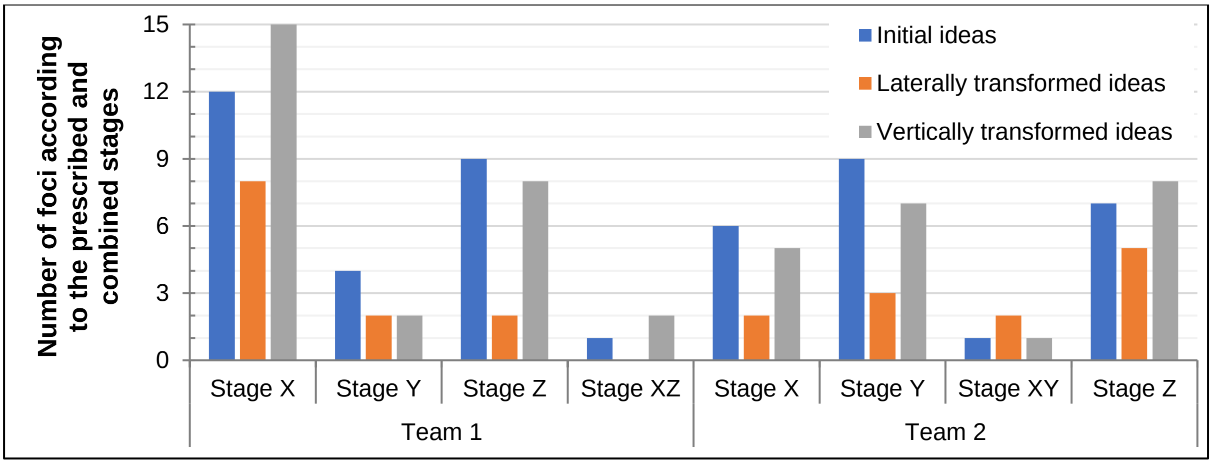


Figure 4.7: Number of the two teams' foci of the different stages

Figure 4.7 indicates the foci of the teams' generated initial and transformed ideas according to the different stages. The participants from Team 1 focused mostly on Stage X with a total of 35 ideas, which was followed by Stage Z with 19 ideas, Stage Y with eight ideas and Stage XZ the least with three ideas. Team 2 focused mostly on Stage Z with a total of 20 ideas, which was closely followed by Stage Y with 19 ideas. This was followed by Stage X with 13 ideas and Stage XY the least with four ideas. It is apparent that the foci distribution of the two teams' generated design ideas are strikingly different from one another. This might have been due to each participants' personal interests in domain-specific knowledge developed from previous design tasks during the course of their Industrial Design studies. Overall, the data indicates how the teams attempted to solve a given ill-structured problem and how their ideas developed during the preliminary design phase. In the following sections, I present evidence of how the participants transformed their generated ideas by systematically discussing an instance from each team with reference to their spoken words and physical external representations.

4.3.1 Team 1's idea transformation structure

During the preliminary design phase, I observed that Team 1 generated and transformed a total of 65 ideas, as indicated in Table 4.2. The foci of these participants' ideas were disproportionately spread between the different stages in which the designed artefact had to perform, which shaped their idea transformation structure. Figure 4.8 illustrates Team 1's idea transformation structure.

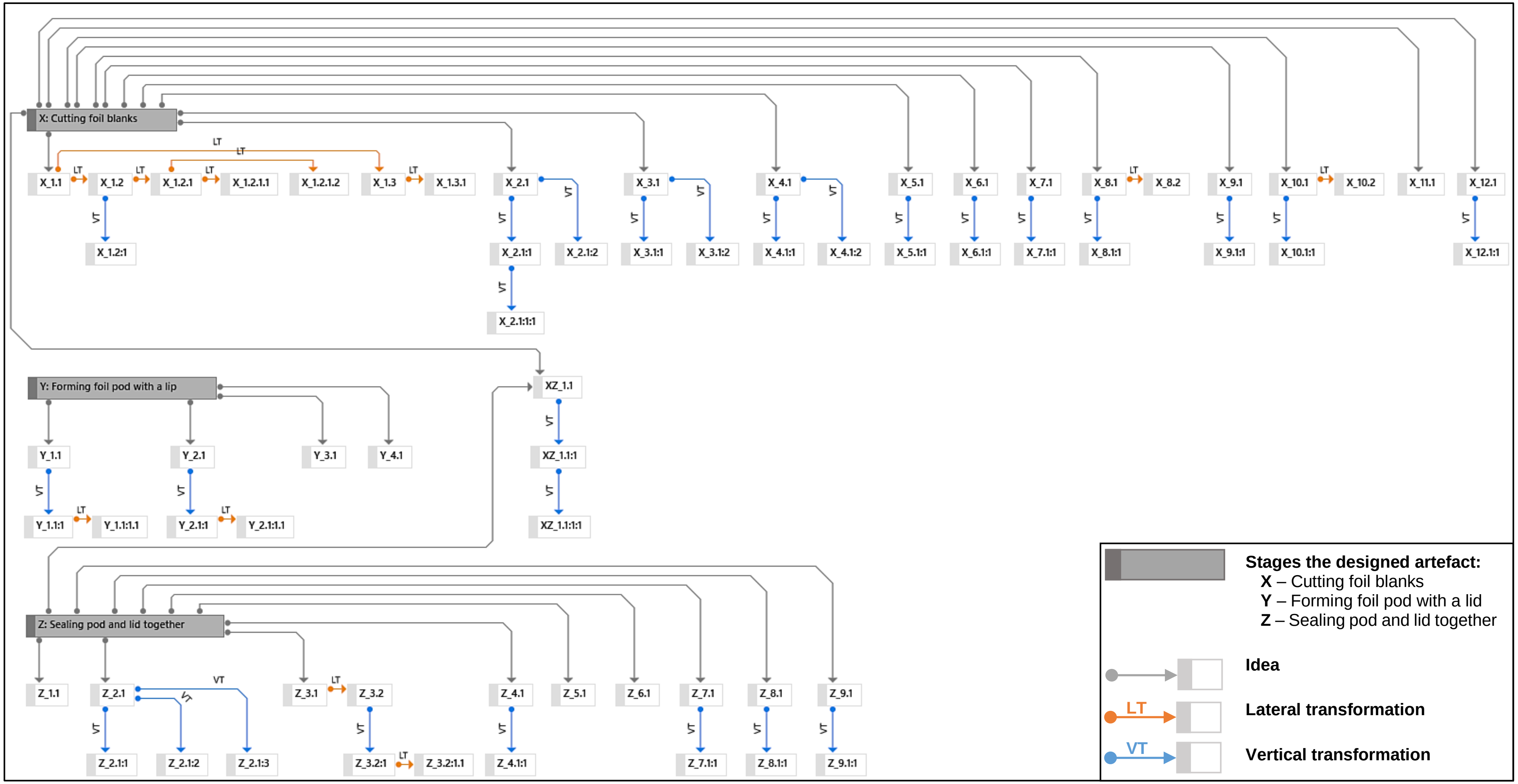


Figure 4.8: Team 1's idea transformation structure during the preliminary design phase of problem solving

Figure 4.8 illustrates the idea transformation structure of Team 1. In the following sub-section, I discuss an instance based on the above transformation structure in which I explore the participants' transformation structure of an instance during Stage Z. In this instance, they generated one initial idea, laterally transformed two ideas and vertically transformed one idea.

Instance from Team 1

Prior to this instance one of the participants from this team explored the idea about engaging the user in sealing aluminium foil coffee pods, captured in Excerpt 4.7. During the following instance, the participants from Team 1 thought about using coffee and a pressing tool to compress form an aluminium foil coffee pod. To this end, the participant were observed to generate one initial idea, two lateral transformed ideas and one vertical transformed idea during their thinking process of Stage Z. The structure of this instance is illustrated in Figure 4.9.

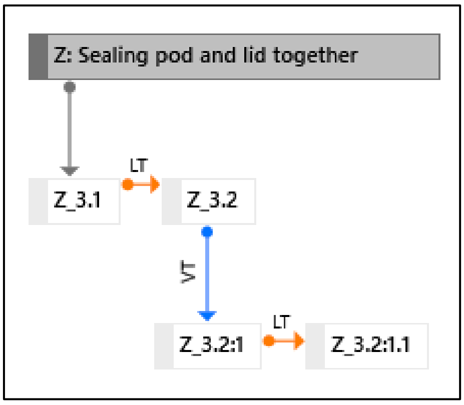
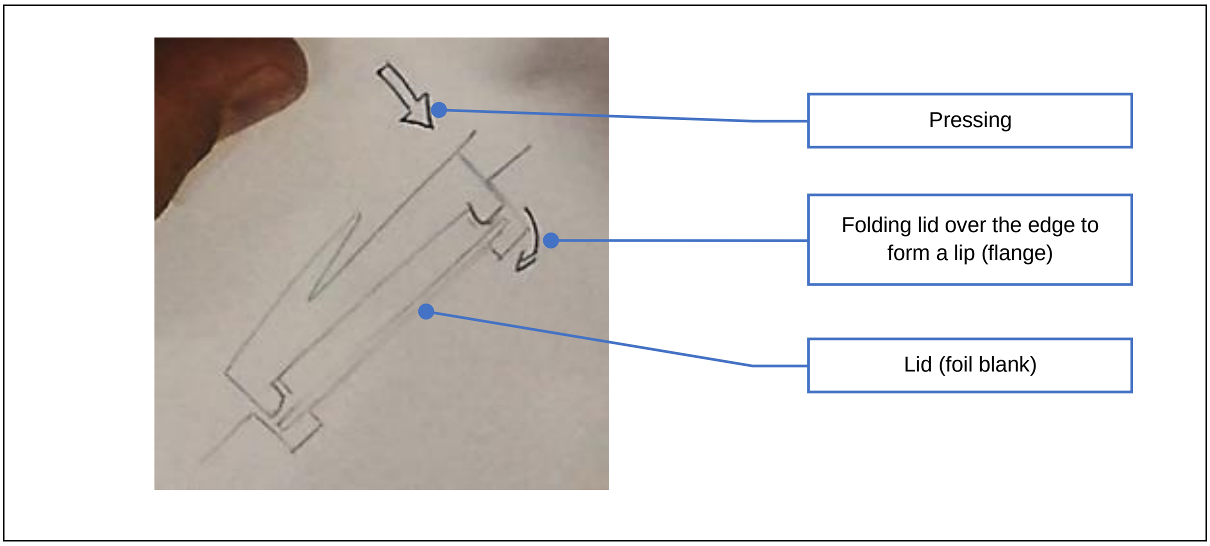


Figure 4.9: Team 1's transformation instance of Stage Z

The instance illustrated in Figure 4.9 consists of a single initial idea that was laterally transformed twice and vertically transformed once. The initial idea (Z_3.1), demonstrated in Excerpt 4.9 and Photograph 4.10 captures the participants from Team 1 proposing an intended function for their envisaged artefact.

Excerpt 4.9

P2 (2:05:48) – Press it through [Z_3.1] … It is round so that it would not cut it, on that edge… and it would fold this down into this little drop. It will fold these edges down. Press, as a second function… No, I'm just erasing that.



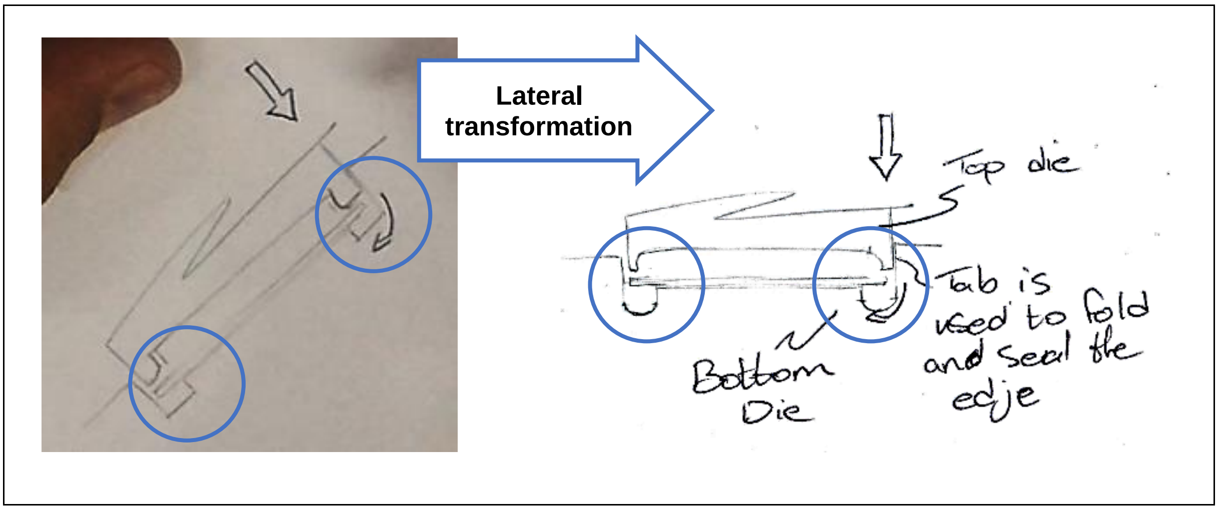
Photograph 4.10: P2's sketch evidencing an initial idea

Excerpt 4.9 and Photograph 4.10 demonstrate the participants' initial idea (Z_3.1) in attempting to provide an intended function to seal aluminium foil coffee pods by making use of a pressing function for folding the lid aluminium foil blank over the edge of the female mould to make a lip. The participant spent a fair amount of time generating this initial idea where he made reference to aspectual intentions, functional intentions and physical elements. During the initial idea, I observed the participants to make various links between intentions: functional intentions ('sealing: folding lid over pod lip' and 'sealing: pressing') linking with the formative aspectual intention; and a physical element ('folded lip over the edge') linking with the formative aspectual intention. These links suggest that the participant was only proposing a function for the envisaged artefact. Since no links were made with physical elements, the participant might have only implied physical elements in order to generate a function intended to seal aluminium foil coffee pods. After proposing a physical structure, the participant thought about changing ("*I'm just erasing that*") the proposed physical structure, as demonstrated in Excerpt 4.10 and Photograph 4.11.

Excerpt 4.10

P2 (2:19:04) – I'm just going to change this… here, and here [Z_3.2]. When it push, when it pushes that thing down, you want it to push more in here. So, you have something… a bit of that, like that. It pushes down like that.

P2 (2:19:58) – This is the top die… and that is the bottom die. Then this tab is used to fold and seal the edge [Z_3.2:1].

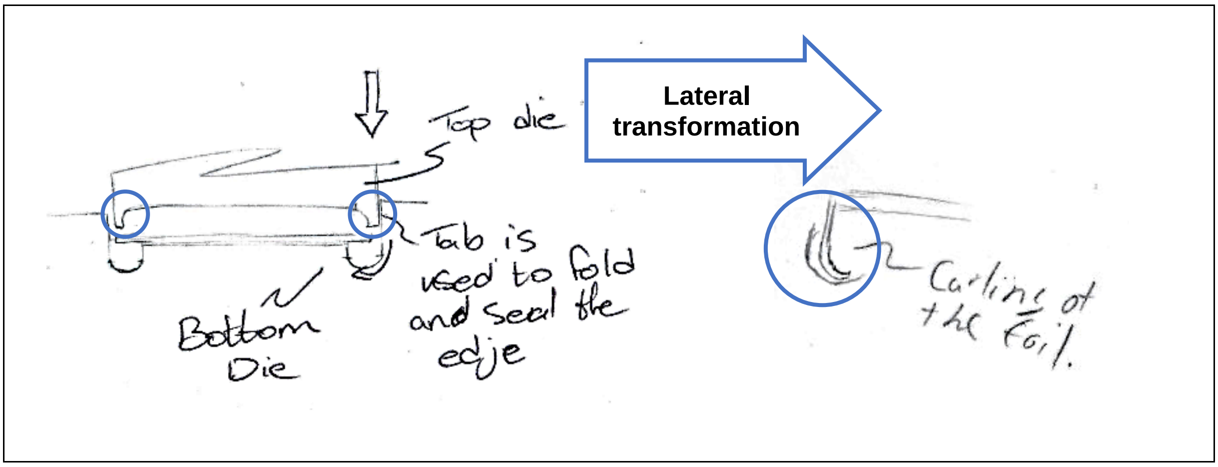


Photograph 4.11: P2’s sketch evidencing a lateral and vertical transformation

Excerpt 4.10 and Photograph 4.11 demonstrates the participant changing the physical structure of the proposed functional intention by laterally transforming (Z_3.2) the initial idea (Z_3.1). The participant, now paying attention to physical elements, realised what he thought to be an error that might prevent the intended function of sealing from taking place. The participant laterally transformed the flat shape parts of the components that presses into one another to be more rounded for the female mould and hook shaped for the male pressing die. During this lateral transformation, the participant made reference to all four hierarchical thinking intentions. However, I observed the participant to link a physical element (‘hook shape’) with a functional intention (‘sealing: folding lip over pod lip’). This link suggests that the participant attempted to find a fit between his intended function and the physical structure, allowing the function to occur. The participant’s implementation intention during this lateral transformation suggests that he found an optimum fit between the intended function and the physical structure. After laterally transforming the initial idea, the idea (Z_3.2) was vertically transformed (Z_3.2:1). During this vertical transformation, no links between intentions were observed. However, the participant added detail to the idea by annotating components and emphasising the function of the components. This suggests that the participant provided a justification for his implementation intention (‘change approach: use hook shape rather than rounded edges to fold lid over lip’). The idea was not further thought about until much later by the other participant from Team 1, as demonstrated in Excerpt 4.11 and Photograph 4.12.

Excerpt 4.11

P1 (3:25:00) – The thing that curls in looks something like this. That piece will come and curl it in [Z_3.2:1.1], something like that… Curling of the foil.



Photograph 4.12: P1's sketch evidencing a lateral transformation

Excerpt 4.11 and Photograph 4.12 demonstrate the other participant from Team 1 changing the proposed physical structure by laterally transforming (Z_3.2:1.1) the previous idea (Z_3.2:1). The participant altered the physical structure by addressing what he thought to be an error, but he unsuccessfully explained the need to change the physical structure. The participant noted that the aluminium foil blank should not only fold over the edge the female mould, but should be curled under the lip of the pressed aluminium foil pod for effective sealing. During this lateral transformation, the participant made reference to aspectual intentions, functional intentions and physical elements. However, I observed the participant to link to a physical element ('folded lip over the edge') linking with the formative aspectual intention. This link suggests an increasing commitment to this design idea amongst the team. However, this idea (Z_3.2:1) suggests that an optimum fit between the intended function and its physical structure had not yet been made since a lateral transformation occurred after an implementation intention was made.

During this instance, the participants incrementally developed their understanding of what was expected of them from the insufficiently specified design brief. Furthermore, the participants attempted to find an optimum fit between their intended function and the physical structure of the envisaged artefact. The participants explored and refined physical elements after the initial idea was made to ensure that their intended function of folding the lid over the lip of the aluminium foil pod could be possible. An increase of detail was observed, which therefore indicates the participants' growing commitment to the design idea (Goel, 1995; Haupt, 2018). The participants continuously evaluated their thoughts through sketch-making, attempting to recognise underlying patterns and possible errors in their envisaged artefact, which indicates their increased commitment. This type of behaviour is typically observed in expert designers (Cross, 2001a, 2004).

4.3.2 Team 2's idea transformation structure

During the preliminary design phase, I observed that Team 2 generated and transformed a total of 60 ideas, as indicated in Table 4.2. The foci of these participants' ideas were unevenly distributed between the different stages in which the designed artefact had to perform, which shaped their idea transformation structure. Figure 4.10 illustrates Team 2's idea transformation structure.

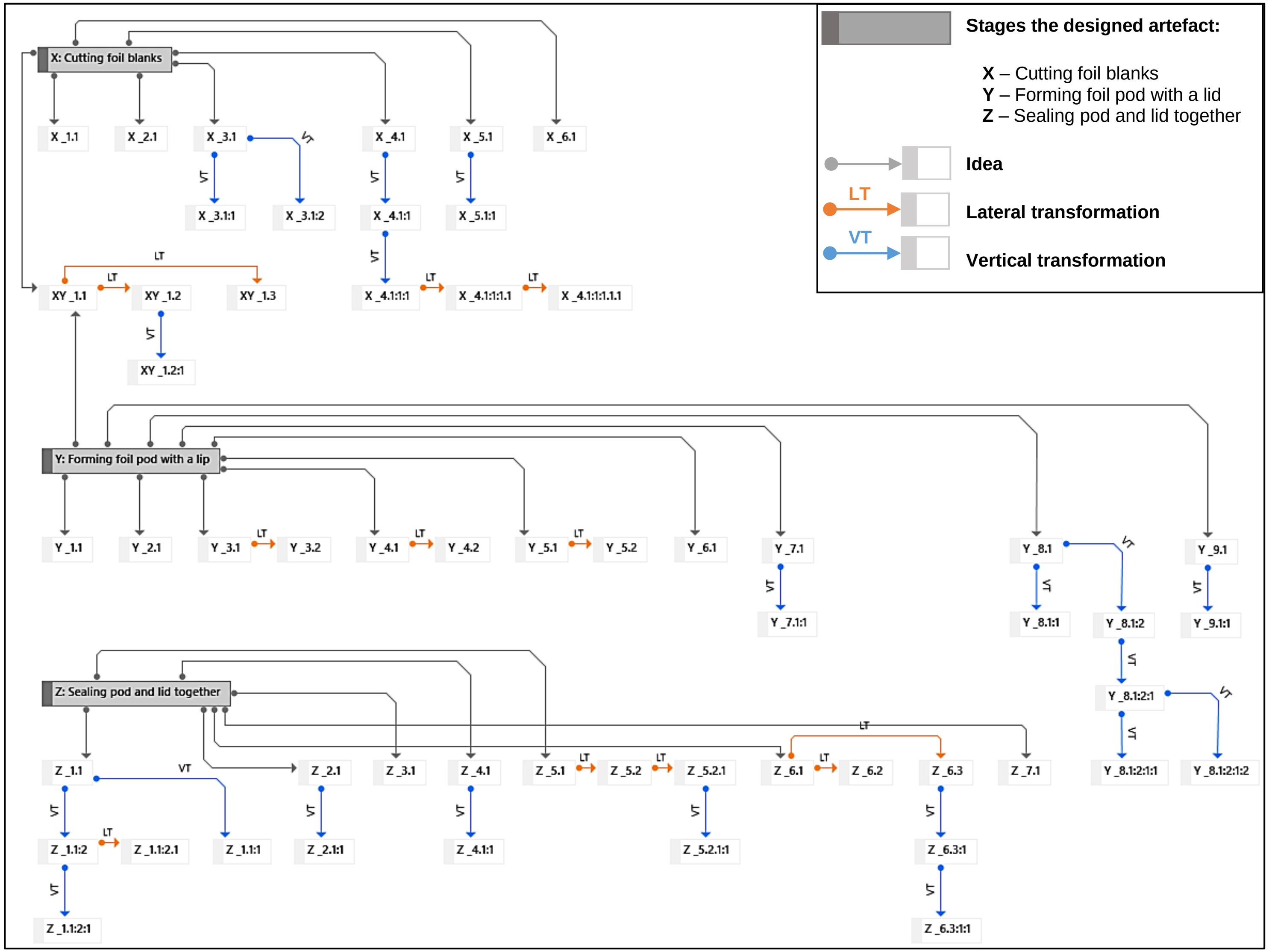


Figure 4.10: Team 2's idea transformation structure during the preliminary design phase of problem solving

Figure 4.10 illustrates Team 2's idea transformation structure. In the following sub-section, I discuss an instance based on the above transformation structure. I further explore the participant's transformation structure during his engagement with Stage Y, where he generated one initial idea, laterally transformed two ideas and vertically transformed one idea.

Instance from Team 2

Prior to this instance, the same participant thought about how coffee could be used to compress form a foil pod by exploring components and shapes *of a coffee pod*, as captured in Excerpts 4.6 and 4.8. During the following instance, one of the participants from Team 2 thought about using coffee and a pressing tool to compress form an aluminium foil coffee pod. To this end, the participant generated one initial idea, from which five vertically transformed ideas emerged during his thinking process of Stage Y. The structure of this instance is illustrated in Figure 4.11.

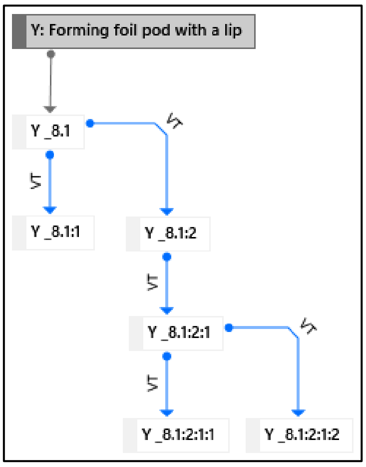
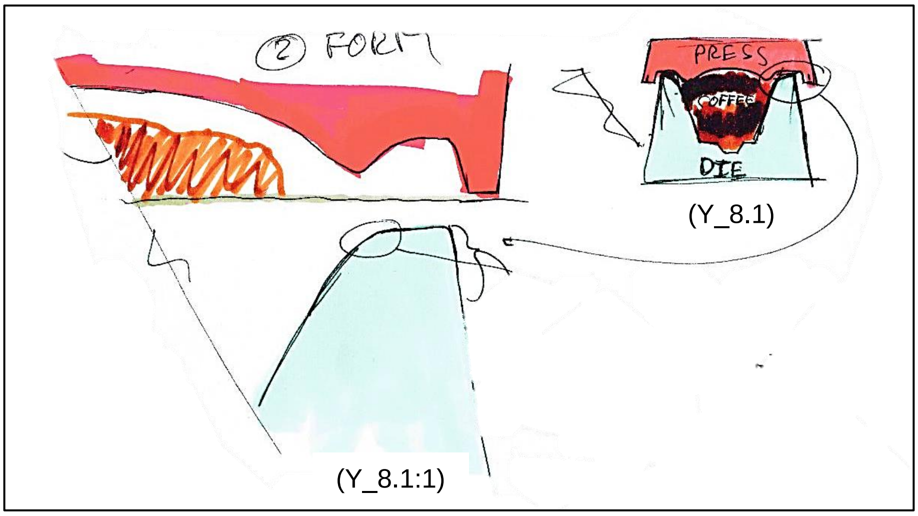


Figure 4.11: Team 2's transformation instance of Stage Y

The instance illustrated in Figure 4.11 consists of a single initial idea that was vertically transformed five times. The initial idea (Y_8.1), demonstrated in Excerpt 4.12 and Photograph 4.13, captures one of the participants from Team 2 proposing a physical structure for an intended function.

Excerpt 4.12

*<u>P4 (3:19:02)</u> – So, this is what our **die** have to look like [Y_8.1], for the aluminium foil, for the pressing. It's going to have rounded corners. Let's write there die. It's going to have rounded corners [Y_8.1:1], so it's going to have the edges off here, and the press tool… like this.*



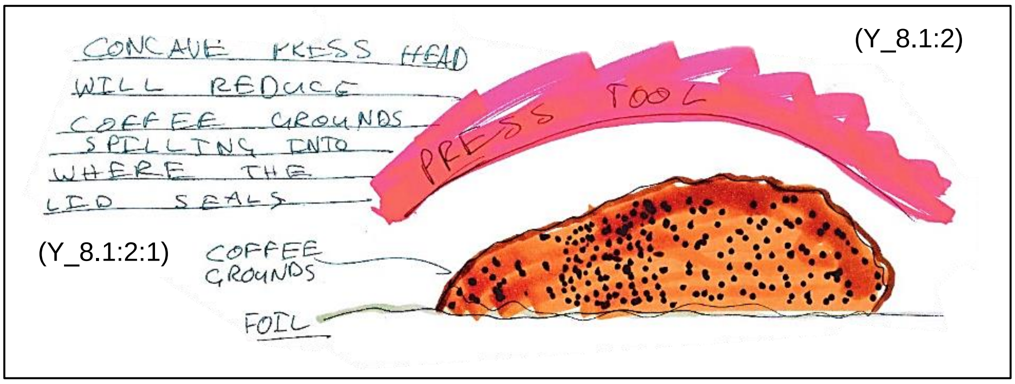
Photograph 4.13: P4’s sketch evidencing an initial idea and vertical transformation

Excerpt 4.12 and Photograph 4.13 demonstrate the participants’ initial idea (Y_8.1), where he attempted to provide a physical structure for the intended function of compress forming aluminium foil pods using ground coffee and a pressing tool. The participant proposed that a female mould (“*die*”) with rounded corners can be used for the intended function of compressing aluminium foil. During this initial idea, the participant made reference to aspectual intentions, a functional intention and physical elements. I observed the participant to link physical elements (‘convex shape’, ‘female mould’ and ‘rounded edges’) with the functional intention (‘pod forming: compress forming’), the functional intention linking with the formative aspectual intention, and a physical element (‘female mould’) with the spatial aspectual intention. These links suggests that the participant was attempting to find a suitable physical structure for the ‘female mould’ and ‘press tool’ that would allow his intended function of compress forming. The participant explicitly made reference to physical elements, suggesting an increased level of commitment to his idea. An increase of detail to his physical external representations was also observed, supporting his commitment.

After the initial idea (Y_8.1), the participant vertically transformed the idea (Y_8.1:1) by sketching part of the proposed physical structure, which included the female mould, the pressing tool and grounded coffee, on a larger scale. During this vertical transformation, the participant made reference to aspectual intentions, functional intentions and physical elements. I observed the participant to make, *inter alia*, similar links to the previous idea (Y_8.1). However, the participant linked a physical element (‘coffee’) with a functional intention (‘pod forming: use coffee for compressing’); and two functional intentions (‘pod forming: compress forming’ and ‘pod forming: use coffee for compressing’) with the formative aspectual intention. These links suggest that the participant attempted to emphasise particular physical elements of the proposed physical structure. The participant’s emphasis seemingly indicated his intention to validate the physical structure proposed for the functional intention. This is evidenced by sketching an upscaled version of the proposed physical structure. Next, the participant thought about how coffee grounds would react when being compress formed, as demonstrated in Excerpt 4.13 and Photograph 4.14.

Excerpt 4.13

P4 (3:22:11) – We have that… aluminium there… coffee there… I’m using colour as an illustrative tool. This is the coffee grounds, and this is the die on top. This is the aluminium foil at the bottom here [Y_8.1:2]. So, foil… press tool… coffee grounds. Concave press head will reduce coffee grounds spilling into where the lid seals [Y_8.1:2:1].



Photograph 4.14: P4’s sketch evidencing two vertical transformations

Excerpt 4.13 and Photograph 4.13 demonstrate the participant vertically transforming (Y_8.1:2) the previous idea (Y_8.1:1) by turning his attention to how the grounded coffee would react when being compress formed using a press tool. During this vertical transformation, the participant made reference to functional intentions and physical elements. I observed the participant to link a physical element (‘coffee’) with a functional intention (‘pod forming: use coffee for compressing’) and another physical element (‘press tool pressing down’) with the other functional intention (‘pod forming: pressing’). These links suggest that the participant attempted to understand what happens with grounded coffee when it is being compress into a mould. Understanding a particular aspect of a design idea is usually associated with problem structuring (Goel, 1995). In this case, understanding how grounded coffee would react suggests a detailing of how the participant's envisaged artefact would function according to a particular physical structure, which implies that leaky modules took place (Goel, 1995).

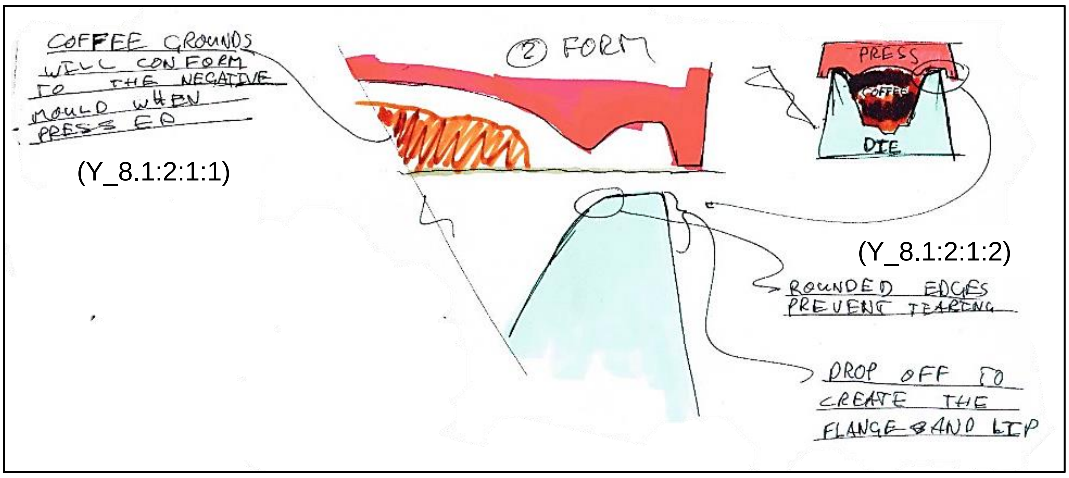
After the vertical transformation (Y_8.1:2), the idea was vertically transformed (Y_8.1:2:1) by detailing his sketch with written text, which acted as the participants' attempt to point out important features to his design idea, such as a 'concave press' that will 'reduce coffee grounds spilling into where the lid seals'. During this vertical transformation, the participant made reference to aspectual intentions, a functional intention and physical elements. I observed the participant to link a physical element ('female mould') with a functional intention ('pod forming: compress forming') and the functional intention with the formative aspectual intention. These links suggest that the participant attempted to emphasise the way in which coffee grounds would react when being compress formed by his proposed physical structure. Next, the participant attempted to explain the fit between his intended function and the proposed physical structure of his envisaged artefact, as demonstrated in Excerpt 4.14 and Photograph 4.15.

Excerpt 4.14

*P4 (3:27:07) – So, now I'm **explaining** why the press tool is like it is.*

P4 (3:28:31) – So, rounded edges [Y_8.1:2:1:1] … Drop-off to create the flange and lip. Coffee grounds will conform to the negative mould when pressed.

P4 (3:33:38) – Rounded edges. Why do I have rounded edges? It will prevent tearing [Y_8.1:2:1:2].



Photograph 4.15: P4's sketch evidencing two vertical transformations

Excerpt 4.14 and Photograph 4.15 demonstrates the participant vertically transforming (Y_8.1:2:1:1) the previous idea (Y_8.1:2:1) by explaining the physical structure of his envisaged artefact. During this vertical transformation, the participant made reference to aspectual intentions, functional intentions and physical elements. I observed the participant to link a physical element ('rounded edges') with a functional intention ('pod forming: compress forming'), another physical element ('lid flange') with the other functional intention ('lip forming: folding foil to make lip), and the functional intention ('lip forming: folding foil to make lip) with the formative aspectual intention. After the vertical transformation (Y_8.1:2:1), the idea was vertically transformed a second time (Y_8.1:2:1:2) when the participant continued explaining the physical structure of his envisaged artefact. During this vertical transformation, the participant made reference to an aspectual intention, functional intentions and a physical element. I observed the participant linking a physical element ('coffee taking the form of the pod') with a functional intention ('pod forming: use coffee for compressing') and the functional intention ('pod forming: compress forming') with the formative aspectual intention. The links from both vertically transformed ideas (Y_8.1:2:1:1 and Y_8.1:2:1:2) suggest that the participant attempted to provide detail to the fit between his intended function and the proposed physical structure. In particular, he referred to certain physical elements, emphasising their importance to the proposed physical structure.

During this instance, the participant firstly explored the spatial aspectual intention by investigating the physical elements of an actual Nespresso coffee pod through sketch making. Thereafter, the participant attempted to find an optimum fit between the intended functions of the envisaged artefact and its physical structure. The participant was observed continuously evaluating his thoughts (Cross, 2001a, 2004) while expressing a high level of commitment by making detailed sketches and providing descriptive written text (Goel, 1995).

4.4 CONCLUSION

The aim of this chapter was to describe the findings attained by tracing the content of novice designers' thoughts to establish whether the connections made are hierarchically organised, as well as how the transformation of their design ideas occurs during the preliminary design phase.

The participants' task involved the design of a hand-held or counter-top hand operative machine that makes cost effective alternatives to Nespresso coffee pods. I contextualised the notion of hierarchical thinking into four levels (aspectual intentions, functional intentions linked with aspectual intentions, physical elements linked with aspectual and functional intentions and implementation intentions linked with functional intentions and physical elements) during the preliminary design phase. The first level demonstrated both teams' consideration of distinct design aspects that give meaning and direction to the way in which they generated, selected and developed design ideas. I established that aspectual intentions served as the participants' driving force behind their design reasoning, emerging from synergistically integrated internal and external sources of information. The second level of hierarchical thinking revealed the participants' intention to define the functional nature of the artefact's purpose, which was insufficiently described by the given design brief. I found that the participants' aspectual intentions took priority over functional intentions when they were engaged with various internal and external information sources, including the design brief, as well as their written words, sketches and physical 3D models. The third level of hierarchical thinking showed how the participants interacted with various internal and external sources of information, which assisted them in understanding the intended function of their envisaged artefact, and recognising what physical elements would appropriately fit their selected aspectual and functional intentions of the artefact they were designing. The fourth and last level of hierarchical thinking demonstrated where the participants' linked their physical elements with aspectual and functional intentions to meet their implementation intentions. Their implementation intentions materialised in the way in which their verbal statements increased in detail and specificity, supported by their written words and hand-drawn sketches, which displayed increased explicitness. I can therefore confirm that hierarchical structures occurred when the teams of participants combined conceptual understanding and perceptual affordances.

During the participants’ idea transformation process, both teams made more or less the same amount of initial ideas and lateral and vertical transformations. Even though the quantity of the teams of participants’ idea generation and transformations were similar, I established that the focus of these ideas differed. This resulted in each team comprising a different idea transformation structure. Team 1, on the one hand, generated and transformed ideas focused on Stage X in which the envisaged artefact had to perform, which was concerned with cutting aluminium foil blanks. Team 2, on the other hand, generated and transformed ideas focused on Stages Y and Z in which the envisaged artefact had to perform, which is concerned with forming and sealing aluminium foil pods. I found that the participants’ consideration of particular abstract aspectual intentions guided the way in which they generated and transformed their ideas based on the different stages in which their envisaged artefact had to perform. I also found that the participants’ need to find a fit between their functional intentions and physical elements allowed them to make both lateral and vertical transformations.

In Chapter 5, I summarise this study and make final conclusions by reflecting on the research questions, based on the conceptual framework of this study, and using the data discussed in this chapter. I thereafter conclude this study by discussing the limitations thereof, and recommendations for future research.

CHAPTER 5: CONCLUSION, LIMITATIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

This chapter presents a synopsis of the preceding chapters, a summary in which the research questions were addressed, and the final conclusions reached as a result of the findings. I also contextualise these conclusions in terms of what has already been found in design cognition studies. After stating the conclusions, I list the potential theoretical and professional practice contributions that this study attempted to make. I specifically emphasise practical guidelines for Engineering Graphics and Design teachers and lecturers, which was one of the main aims of this study, as discussed in Chapter 1 (Section 1.5). Finally, I conclude this chapter by stating possible limitations and how I addressed them, as well as presenting recommendations for future research and educational programmes in design.

5.2 OVERVIEW OF THE STUDY

It has been commonly assumed that designing is an information intensive cognitive activity driven by designers' internal and external information, which is systematically transformed into physically embodied external representations. However, the CAPS document prescribed by the South African Department of Basic Education (2011a) for EGD appears to lack instructional guidelines to facilitate EGD learners' idea transformation capabilities. Therefore, the purpose of this study was to empirically study the behaviour of novice industrial designers during the preliminary design phase to suggest practical guidelines for improving EGD learners' idea generation. Figure 5.1 illustrates a brief overview of this study.

OVERVIEW OF THE STUDY

Research problem

The seeming lack of instructional guidelines for effective facilitation of learners' design cognition in the Engineering Graphics and Design CAPS document.

Research questions

How does novice industrial designers' hierarchical thinking support the development of their idea transformations during the preliminary design phase?

1. How do novice industrial designers' aspectual intentions support their idea transformations during the preliminary design phase?
2. How do novice industrial designers' functional intentions support their idea transformations during the preliminary design phase?
3. How do novice industrial designers' physical elements support their idea transformations during the preliminary design phase?
4. How do novice industrial designers' implementation intentions support their idea transformations during the preliminary design phase?

Conceptual framework

- Hierarchical thinking levels: aspectual intentions, functional intentions, physical elements and implementation intentions.
- Idea transformation: Initial ideas and laterally and vertically transformed ideas.

Research methodology

Mixed methods, case study, third-year Industrial Design participants, In-vivo methodology, video recording, verbal data, visual data, temporal data.

Data structuring and analysis

Macro-level analysis

- Sub-level 1: Code time frame
- Sub-level 2: Overview of identified events

Meso-level analysis

- Sub-level 3: Identify significant events and code episodes and segments

Micro-level analysis

- Sub-level 4: Code a-priori hierarchical thinking levels
- Sub-level 5: Code a-priori idea transformations

Findings

- The participants predominantly focused on the formative, spatial and kinematic aspects from the identified eight aspectual intentions.
- The participants predominantly made functional intention links with the formative aspectual intention.
- The participants predominantly made physical element links with functional intentions than with aspectual intentions.
- The participants predominantly made more implementation intention links with functional intentions than with physical elements.
- The participants' consideration of particular abstract aspectual intentions guided the way in which they generated and transformed their ideas.
- The participants experienced a need to find a fit between their functional intentions and physical elements, allowing them to make both lateral and vertical transformations.

Figure 5.1: Overview of this study

In Chapter 1, I outlined the focus of this study, which was to describe how novice industrial designers make links between different levels of hierarchical thinking and support the development of their idea transformations. I therefore formulated the following primary research question that guided the planning and implementation of this study:

How does novice industrial designers' hierarchical thinking support the development of their idea transformations during the preliminary design phase?

In Chapter 2, I conducted a literature survey on design cognition in the field of Industrial Design (Haug, 2015; Kruger & Cross, 2006; Laing & Masoodian, 2016; Lu, 2015; Vasconcelos et al., 2016), as well as the literature regarding hierarchical thinking (Allen & Starr, 2018; Gero & Kannengiesser, 2004; Medland, 2007; Vermaas, 2009; Wu, 2013) and idea transformations (Chen et al., 2003; Goel, 1995; Hegeman, 2008; Rodgers et al., 2000). Thereafter, I reviewed literature on Extended Design Cognition (Clark & Chalmers, 2010; Shani, 2013), which was informed by integrating Information Processing theories (Goel, 1995; Newell & Simon, 1972) and Ecological Psychology (Gibson, 1977; Richardson, Shockley, Fajen, Riley, & Turvey, 2009; Young, 2004). External Design Cognition was used as the meta-theory for this study in order to describe novice industrial designers' design cognition, specifically, how they utilised internal and external information sources to make various links between the different hierarchical thinking levels and lateral and vertical transformations. I concluded the chapter by discussing the conceptual framework that I used in order to investigate and describe the participants' links between the different levels of hierarchical thinking, supported by their transformation of ideas. The conceptual framework was additionally used to guide my methodological decisions, which, in turn, provided me with a roadmap to address the research questions.

In Chapter 3, I outlined the research methodology of the study. In order to generate qualitative and quantitative data that could be analysed and interpreted qualitatively, I applied a case study research design that was embedded in a concurrent mixed methods research approach. A design task, crafted by the participants' responsible Industrial Design lecturer, was used to elicit the design cognition of each team of participants. Subsequently, I followed an adapted in-vivo methodology to capture the verbal and visual representations of the participants' cognitive actions during the preliminary design phase of the design process. In order to structure, analyse and interpret the captured data, I adapted the Discourse Analysis methodology from Ash (2007), which consisted of three levels, namely, macro-level, meso-level and micro-level analysis. This enabled me to systematically work through the data, where I identified the teams of participants' attention to the various hierarchical thinking levels, as well as their idea transformation structure.

In Chapter 4, I presented evidence of the Industrial Design student participants' hierarchical thinking and the transformation of ideas. I interpreted the data by discussing how links were made between the various hierarchical thinking levels and how these intentions supported the participants' transformation of ideas. I ended the chapter by discussing how each team of participants made idea transformations during the preliminary design phase.

5.3 Conclusions in terms of the secondary research question

In the following section, I discuss my conclusions by relating the findings to the five secondary research questions of this study. As such, I indirectly address the primary research question.

5.3.1 Secondary research question 1: How do novice industrial designers' aspectual intentions support their idea transformations during the preliminary design phase

This study established that the novice designers considered distinct design aspects that gave meaning and direction to the way in which they generated initial ideas and transformed these ideas, being committed to some and rejecting others. Using the 15 aspects from Dooyeweerd's Theory of Aspectual Modality of Reality (Basden, 2011), I identified the particular aspects that played a role in the novice designers' design thinking. Overall, the aspectual intentions that received the most attention during the preliminary design phase were the formative aspect, followed by the spatial and kinematic aspects. These aspectual intentions were observed to lack specificity in the novice designers' verbal utterances. This suggest that novices, like experts, have the capability to choose and follow particular aspects, and disregard others without rejecting their validity (Haupt, 2018). This further means that the laws of particular design aspects were typically implied by the novice designers and not specifically explicated. Aspectual intentions therefore served as the novice designers' driving force behind their idea transformation, which emerged as they interacted with internal and external sources of information. This allowed the novice designers in this study to generate initial ideas and make lateral transformations in order to explore alternatives that could solve the given ill-structured design problem.

5.3.2 Secondary research question 2: How do novice industrial designers' functional intentions support their idea transformations during the preliminary design phase

In terms of functional intentions as the second level of hierarchical thinking, this study revealed that novice industrial designers typically seek to define the function or purpose of the artefact being designed. In doing so, the novice designers attempted to supplement the insufficient and unspecified information provided by the ill-structured problem in the design brief in order to explore functionality and derive the functional requirements expected to be achieved (Goel, 1995; Haupt, 2018). Functional intentions were seemingly triggered by the novice designers' consideration of particular aspectual intentions. Overall, the aspectual intentions that were mostly considered while exploring functionality were the formative aspect, followed by the kinematic aspect. Exploring functionality while considering the formative aspectual intention was not surprising since the formative aspect is concerned with the deliberate shaping of things (Basden, 2011). The shaping of things in this sense did not refer to physically structuring the novice designers' envisaged artefact, but rather exploring the functions that their envisaged artefact could perform in order to shape things. Based on the findings of this study, novice designers' consideration of aspectual intentions seem to take priority over their functional intentions. This meant that the novice designers' aspectual intentions informed and guided the way in which they thought about functionality. This, in turn, allowed the participants to vertically transform their abstract ideas into semi-concrete ideas.

5.3.3 Secondary research question 3: How do novice industrial designers' physical elements support their idea transformations during the preliminary design phase

In terms of physical elements as the third level of hierarchical thinking, this study revealed that novice industrial designers typically make statements about the physicality of the artefact being designed. In doing so, the novice designers attempted to provide their functional intentions with a suitable physical structure which, by implication, met with their abstract aspectual intentions. Based on the findings of this study, I established that the novice designers explored physical elements by linking these to both their aspectual and functional intentions. Overall, the novice designers were observed to spend more time linking physical elements with functional intentions than linking physical elements with aspectual intentions. This meant that the participating novice designers attempted to find an optimum fit between their intended functions and a physical structure suitable for the requirements to be achieved. This included their intention to find a suitable structure for the intended function of their envisaged artefact, as well as a structure for the envisaged artefact in which the intended function could operate, but also to understand the structure of the product their envisaged artefact had to produce. The novice designers' statements about physical elements allowed them to transform their ideas both laterally and vertically. As the novice designers transformed their abstract aspectual intentions and semi-concrete functional intentions into detailed expressions about physical elements, the level of explicitness in their physical external representations and amount of specificity in their verbal utterances increased.

5.3.4 Secondary research question 4: How do novice industrial designers' implementation intentions support their idea transformations during the preliminary design phase

In terms of the last level of hierarchical thinking, the literature in Chapter 2 explains that novice designers make implementation intentions to make choices that they think will support them in meeting the requirements to be achieved. The distinguishing characteristic of intentions consisting of implementation thoughts is the reference to an activity that is more specific than the preceding intentions, for example, 'you can put coffee in the shaft, and it will form the pod when compressed directly into the die'.

The articulation of such choices indicated the novice designers' intention to implement an intended function or physical structure with their envisaged artefact (Haupt, 2018). This study revealed that the participating novice designers from both teams had definitive instances where their implementation intentions were linked with both functional intentions and physical elements. In this study, the novice designers made more implementation intentions based on their functional intentions than with their intended physical elements. I found that when the participants attempted to find an optimum fit tween their intended functions and a suitable physical structure for their envisaged artefact, they tended to redefine their previously made functional intentions rather than exploring an alternative physical structure that would accommodate their functional intentions. The novice designers applied trial-and-error techniques to explore parts of the problem in detail until they reached consensus and made appropriate choices (Cross, 2001a). This indicated that the novices' implementation intentions served as a saturation point in their design thinking (Haupt, 2018), which is characterised by an increased level of detail and specificity as their verbal utterances incrementally materialised. This was seen in instances where the novice designers typically made lateral transformations before making vertical transformations. The concluding vertical transformations of these instances typically consisted of implementation intentions, which were supported by their physical external representations.

5.4 CONTRIBUTIONS OF THE STUDY

In this section, I describe the contribution this study may make towards theories of design cognition and the professional practice of design-related subjects. In this way, I address my primary research question.

5.4.1 Theoretical contribution

The primary research question of this study, namely, '*How does novice industrial designers' hierarchical thinking support the development of their idea transformation during the preliminary design phase?*', implies not only confirmatory results from previous studies (Dubery, 2015), but also a potential theoretical contribution to theories in design cognition. This study revealed that novice designers' hierarchical thinking guided how they generated initial ideas and supported how they transformed these design ideas. This study confirms previous findings and contributes additional evidence that suggest a slightly different structure than the original hierarchical thinking model, suggested by Haupt (2018), to support novice designers' idea transformation process during the preliminary design phase. Figure 5.2 illustrates the hierarchical thinking structure based on the findings of this study.

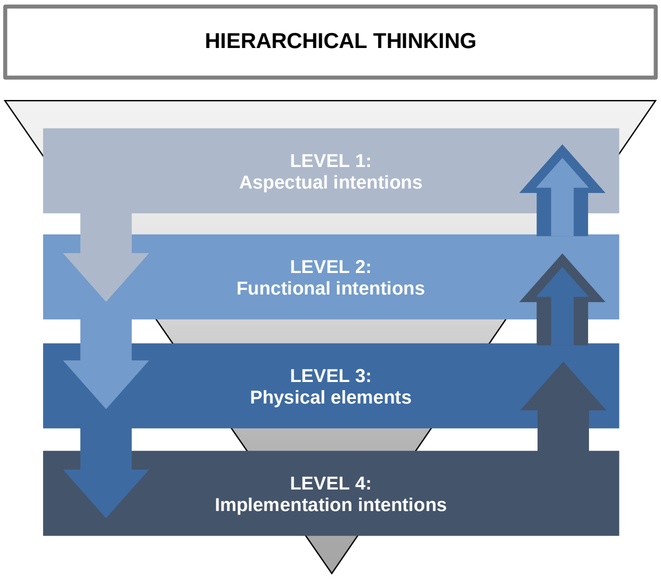


Figure 5.2: Hierarchical thinking structure based on the findings of this study

Figure 5.2 illustrates the hierarchical thinking structure based on the findings presented in this study. This hierarchical thinking structure, like the original hierarchical thinking model from the conceptual framework (Section 2.6), works in a top-down manner. This study revealed that during novice industrial designers' hierarchical thinking processes, they typically make the following multi-directional links between the various levels of intentions:

- Functional intentions and aspectual intentions,
- Physical elements and aspectual intentions,
- Physical elements and functional intentions,
- Implementation intentions and functional intentions, and
- Implementation intentions and physical elements.

Each of these links indicated how the novice designers generated initial ideas and transformed selected ideas. This, in turn, confirms the suitability of a four-level hierarchical thinking model (Haupt, 2018) to trace and map novice designers' thought processes and cognitive behaviour.

5.4.2 Professional practice contribution

The professional practice contribution of this study may be seen as an opportunity for design educators to develop design activities in which students are made aware of hierarchical thinking and the transformation of ideas. Based on the findings of this study, potential practical applications can be contributed to EGD. Making learners consciously aware of these hierarchical levels and how these levels link with one another might allow teachers to facilitate learners' idea transformation process. I therefore make the following pedagogical guidelines that could assist EGD teachers to facilitate learners' design thinking.

Aspectual intentions act as a guiding mechanism for generating initial ideas and making lateral transformations. These allow novice designers to explore alternatives that could solve ill-structured design problems. For teachers, this implies that when formulating design tasks, they should consider some of Dooyeweerd's 15 aspects of reality (Basden, 2011), as a guiding structure. In doing so, they could facilitate learners' hierarchical thinking processes, while teaching learners to be comfortable with uncertainty. Furthermore, this will allow teachers to provide learners with the necessary relevant information in the design brief, even though the design problems are still of an ill-structured and ill-defined nature, to guide their problem-solving activities. In turn, this could potentially assist learners not to focus on and explore concrete features of a given design problem in-depth, as generally done by novice designers (Cross, 2004, 2011).

Functional intentions allow novice designers to explore functionality by vertically transforming their abstract aspectual intentions. For teachers, this implies that they should be able to recognise moments when learners are too engaged with making vertical transformations early in the design process. Making more vertical than lateral transformations can increase the tendency of learners fixating (Chen et al., 2003; Rodgers et al., 2000). In order to prevent the possibility of fixation, teachers could ask their learners questions about their functional intentions with regard to some of Dooyeweerd's 15 aspects of reality (Basden, 2011). In doing so, teachers would allow learners to think of alternative ideas which in turn enables them to make lateral transformations to deviate from potential fixated ideas. In this way, learners would consider various design aspects simultaneously to which they could, through trial-and-error techniques, derive alternative functional intentions for their envisaged artefact.

Physical elements allow novice designers to propose an intended physical structure for their envisaged artefact and explore the fit between their intended function, as well as their aspectual intentions by making lateral and vertical transformations. For teachers, this implies that they could guide learners' exploration by asking them questions about the dual nature of their envisaged artefact (Kroes & Meijers, 2006). Questions like such should address learners' intended function and the physical structure of their envisaged artefacts, for example: (a) '*do you understand the physical structure of product that your envisaged artefact have to produce?*'; (b) '*does your intended physical structure suit the intended function of your envisaged artefact?*'; and (c) '*does your intended physical structure suit your envisaged artefact in which the intended function could operate?*'. By asking questions like these could allow learners to make lateral and/or vertical transformations for achieving the dual nature of their envisaged artefact.

Implementation intentions allow novice designers to make choices about the fit between their intended function and physical structure by making lateral and vertical transformations. For teachers, this implies that they should guide learners' decision-making processes by asking them to explain, and/or demonstrate, the dual nature of their envisaged artefact using their physical external representations. If a learner, or the teacher, realise that the fit between the learners' intended function and physical structure is not yet reached, the learner could make the necessary lateral and/or vertical transformations in order to achieve the dual nature of his/her envisaged artefact. In this way, teachers allow learners to solve the given design problem through trial-and-error techniques, as well as allow the learners' design thinking processes to reach saturation point (Haupt, 2018).

These above mentioned guidelines might allow EGD learners, as well as EGD students, to structure their problem-solving activities and reduce cognitive load. In order to facilitate this, I recommend design educators to consider adapting General Morphological Analysis, which is described in Section 5.6.1.

5.5 LIMITATIONS OF THE STUDY

In this section, I report on the limitations that I encountered during the course of this study in terms of sampling, data capturing and data analysis.

5.5.1 Sampling

This study was limited to four top-achieving third-year Industrial Design students working in teams of two. The challenge was to select a sampling method that ensured that the selection of participants was representative of the top-achieving third-year Industrial Design students. I therefore selected a small, purposeful sample with the assistance of the responsible Industrial Design lecturers. The sample selection criteria included participants' ability to smoothly apply their knowledge and skills to the design process, articulate their thoughts aloud when engaged with given design activities, and use both critical and creative thinking to resolve the diverse requirements of users, manufacturers and the environment. This set of criteria was used in order to select a non-discriminatory sample from which much could be learned. Furthermore, the small sample did not allow me to generalise the findings, and consequently there is a danger of non-representativeness. My decision to limit the sample size was due to the large amount of information generally generated in cognitive research. Selecting a larger sample would make reporting impractical, which therefore may have compromised the credibility of this study.

5.5.2 Data capturing

A potential limitation of this study was the utilisation of in-vivo methodology to capture data in an authentic Industrial Design studio environment. In my preliminary investigation of the Industrial Design studio of a local University of Technology as the research site, I observed multiple factors such as noise levels, interruptions, and interactions with teachers and peers, which might have compromised the richness of the data being captured. With the permission of the responsible lecturers, a separate working space within the naturalistic Industrial Design studio environment was set up in which the teams of participants could work in order to capture the data produced by the participants through an in-vivo approach. This enabled me to minimise background noise and non-participant interference, as well as ensuring a conducive environment for problem solving.

A further limitation of this study was the use of camera equipment while capturing data. The challenge I faced while capturing the data was that the GoPro action cameras would occasionally freeze and shut down, saving corrupted recordings. This problem typically occurred when participants entered low-lit areas within the Industrial Design studio, and was further caused by overheated cameras continuously recording for hours at a time. The data captured in the corrupted recording files were lost. However, having multiple cameras recording the teams' design behaviour, I was fortunate to recover most of the information from the lost data by reviewing the team members' recordings.

5.5.3 Data analysis

Using a QUAL-quan mixed methods research strategy, as discussed in Chapter 3, posed certain limitations on analysing the large amount of data generated by the participants. Coding the large amount of complex data in a manner that was practical and meaningful was very time-consuming. However, I asked knowledgeable experts in the field of design cognition to scrutinise the coding procedure and interpretation in addition to my own readings and re-readings of the teams of participants' produced data, ensuring validity and reliability.

A further limitation of this study was that I faced the risk of reducing the complexity of the study. Through the use of a mixed methods approach, I therefore attempted to successfully represent the complexity of the teams of participants' design cognition. The representation of the teams' complex design cognition was achieved through triangulation, correlating the qualitative and quantitative data sets with one another. Representing the complexity of the participants' design cognition provided the study with richness, depth and the confirmation of findings and the interpretations thereof.

5.6 RECOMMENDATIONS OF THE STUDY

In this section, I offer recommendations for educational programmes in design and further research in light of the findings presented in this study.

5.6.1 Recommendations for educational programmes in design

I recommend that educational programmes in design develop tools based on hierarchical thinking and idea transformation to be used for formulating design tasks. These tools should allow educators to craft design tasks where students are expected to intentionally pay attention to their various levels of hierarchical intentions. Students being consciously aware of their hierarchical thinking levels might allow them to make cognitive links between their intentions while actively being engaged with the physical environment to look for missing information that could augment their idea transformation process. However, care should be taken in order to minimise students' tendency to fixate.

In addition, I recommend that design educators consider adapting the General Morphological Analysis (GMA), developed by Zwicky (1969), when formulating design tasks. In essence, GMA is a typological methodology used to identify and define parameters of a given problem, in order to investigate a set of possible relationships or configurations contained in a given problem (Ritchey, 1998b). A problem is typically structured by setting the parameters against one another in a n-dimensional matrix called a morphological box or multi-dimensional matrix (Ritchey, 1998a). An example of a morphological box is illustrated in Figure 5.3.

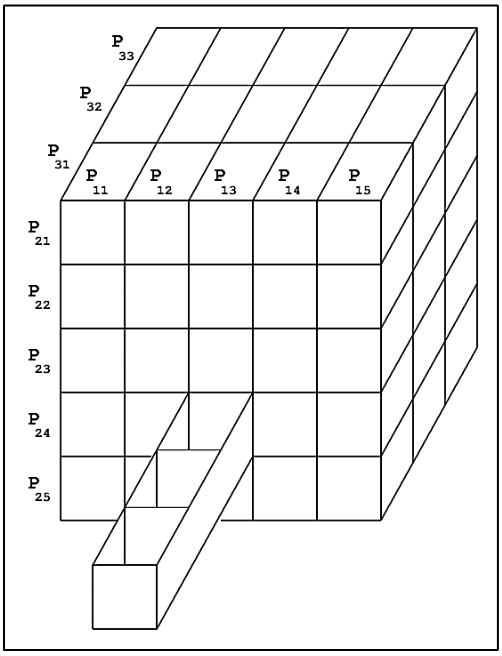


Figure 5.3: A 3-parameter morphological box (Zwicky, 1969)

Figure 5.3 illustrates a morphological box consisting of 3 parameters, each with a set of conditions. These parameters, for example, could include Dooyeweerd's 15 aspects of reality (Basden, 2011) as the first parameter, and the dual nature of artefacts (Kroes & Meijers, 2006) as the second and third parameters. Therefore, the first parameter contains 5 design aspects, the second parameter 5 functions, and the third parameter 3 physical structure. As such, the morphological box (5×5×3) consists of 75 cells, which implies that there are 75 configurations. Each configuration emphasises particular focus on a single design aspect, function and physical structure. In this regard, design educators could select a configuration in which they want their students to be assessed. Design educators following a morphological approach, promotes an unbiased manner in which design problems can be formulated from (Ritchey, 1998b).

5.6.2 Recommendations for future research

The research that has been conducted in this study highlights a few areas that might be beneficial and worthwhile to pursue, and therefore I recommend the following studies:

- Case studies replicating this study in the context of other design domains, such as architecture, engineering and fashion design, to cover a wider novice design population, allowing for generalisation.
- Quasi-experiment studies determining the role that design tasks play in the way in which novice designers give attention to the different hierarchical thinking levels during the early phases of the design process.
- Ethnographic studies investigating how design educators make students consciously aware of the various hierarchical thinking levels during design tasks, allowing the facilitation of design cognition.

5.7 Conclusion

In this chapter, I presented a synopsis of the research conducted. I firstly provided a brief overview of the study by presenting discussions from the preceding chapters. This was followed by a discussion of the findings of this study in which I addressed the research questions. Thereafter, I presented the scope of contributions that might arise from the findings. I concluded this chapter by reporting the limitations of this study and discussing recommendations for future research.

The purpose of this study was to explore and describe how novice industrial designers' hierarchical thinking supports their idea transformation process during the preliminary design phase. From the findings of this study, I could conclude that the participants' hierarchical thinking supported and shaped their idea transformation process. This implies that educators can play a significant role in facilitating design students' design cognition by making them consciously aware of the various levels of intentions and how to utilise these intentions to guide their idea transformation processes. If we want design students to develop higher-order design cognition, we should encourage current and future educators to craft design tasks in which students could consciously exercise making links between their hierarchical levels, thus supporting their lateral and vertical transformations.

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LIST OF APPENDICES

APPENDIX A – PERMISSION TO CONDUCT RESEARCH

A1 – Letter requesting permission (Hard copy & CD)

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Education

FACULTY OF EDUCATION
Department of Science, Mathematics and Technology Education
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[redacted]

REQUEST PERMISSION TO CONDUCT RESEARCH AT [redacted]

Dear [redacted]

My name is Stiaan Kamffer, and I am currently enrolled for my M.Ed. (Masters) in the Faculty of Education, University of Pretoria. I have to complete a research module which requires me to conduct empirical research and write a research dissertation about my work. I hereby request your permission to conduct research in the Department of [redacted].

The title of my research is: *The cognitive role of mock-ups in novice industrial designers' hierarchical thinking process*. The purpose of this study is to explore and describe how graphic communication strategies used during the design process aid the design thinking process of Industrial Design students in their third year of study, when conceptualising an idea during the problem solving space. Conducting research on the cognitive behaviour of Industrial Design students and how various graphic communication strategies might foster their design thinking abilities, might enable me to understand what is needed in the national Curriculum and Assessment Policy Statement for Engineering Graphics and Design, in order to prepare Further Education and Training pre- and in-service teachers to guide learners for entering tertiary design profession studies.

My study's aim is thus to provide guidance to the Engineering Graphics and Design curriculum developers to make provision for a more balanced distribution of focus on a variety of graphic communication strategies. However, potential benefit for [redacted] in general and in particular for the participating students, which might result from this study, is the contribution towards a better understanding on how to improve education for Industrial Design students. Participating students might potentially benefit from developing a self-awareness of their own design process as well as their own reasoning skills for solving socio-technological design problems.

If you grant me permission to conduct the proposed research in the Department of [redacted], I will observe eight top-achieving third year Industrial Design students while completing their design projects required by their relevant lecturers. The selection of top-achieving students is based on the premise that higher order design cognition in tertiary education is more likely to be found in top-achieving students than in weaker performing students. In addition, third year Industrial Design students are still considered as novices in the respective design profession. Observations will be conducted over a period of two weeks during the last week of January 2018 and the first week of February 2018. The observations will be video-recorded at Pretoria Campus in the Industrial Design studio between 8:00 and 14:00. Observations will only be conducted on particular days during the

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Lefapha la Thuto

two week timeframe and will last approximately 6 hours each. This will be pre-arranged with the relevant lecturers in the department. I will do my utmost to minimise inconvenience and disruption of the formal learning process involved. Although the relevant lecturers of Industrial Design department will assist me in selecting suitable participating students, they will not participate in this study. The students' academic performance should be based on the subject Industrial Design II ([redacted]).

The eight selected students will be grouped into pairs and asked to participate in my study, each pair at the same time. Each pair will be asked to verbalise their thoughts and make sketches and mock-ups in to develop an understanding and find a possible solution to a design problem. The task containing the design problem will be provided by the responsible lecturer for the third year students. The observations will be video and audio recorded and transcribed by me for analytical purposes. Only my supervisor and I will have access to this information. The relevant students will be fully informed about this procedure and their informed consent will be obtained. The gathering of data will only commence once all these have been granted and all the requirements of the Ethical Committee of the University of Pretoria have been met.

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 University and identities of the participants will be treated confidentially, and will not be disclosed.
2. The video recording transcripts will be treated confidentially. Only the student and the supervisor will have access to the audio-video recordings 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 unrecognisable and censored.
4. Only the student will know the identity of the students who agreed to participate in the study.
5. Pseudonyms for the university and students will be used in all spoken and written reports.
6. The information provided by the students 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 students will not be exposed to acts of deception at any point in the research study.
9. The students will not be placed at risk of any kind.
10. No incentives will be offered to any of the research participants.
11. The videographer(s) involved in the research study will be trained in all matters of ethics, and in particular, confidentiality and anonymity.

The collected data will be locked up for safety and confidential purposes in either my or my supervisor's possession. The results of this study may be presented at conferences or published in scientific journals. After completion of this study, the data will be stored for fifteen years at the Department of Science, Mathematics and Technology Education, University of Pretoria.

Should you agree to allow me to conduct this study at your university, please complete the permission form provided below.

For any further queries, please do not hesitate to contact me or my supervisor at the contact details provided below.

Your support in this matter is much appreciated.

Mr. Stiaan Kamffer (student)
084 569 6827
stiaan.kamffer@up.ac.za

Dr. Grietjie Haupt (supervisor)
(012) 420 5631
grietjie.haupt@up.ac.za

A2 – Permission from Faculty Executive Dean (Hard copy & CD)

Permission form

I, [redacted] (your name only), Executive Dean for the Faculty of [redacted] at [redacted] agree to the research project titled, *The cognitive role of mock-ups in novice industrial designers' hierarchical thinking process*, be conducted in the Department of [redacted]

I hereby give permission for six third year Industrial Design students to be video recorded and observed for approximately six hours at the Pretoria Campus in the Industrial Design studio during the last week of January 2018 and the first week of February 2018.

I understand that the Industrial Design lecturers will not take part in this study, but will be asked to identify six third year students that are top achievers in the subject Industrial Design II.

I understand that the researcher subscribes to the principles of:

- *Voluntary participation* in research, implying that the participants might withdraw from the research at any time.
- *Informed consent*, meaning that research participants must at all times be fully informed about the research process and purposes, and must give consent to their participation in the research.
- *Safety* in participation; put differently, the human respondents should not be paled at risk or harm of any kind.
- *Privacy*, meaning that the *confidentiality* and *anonymity* of human respondents should be protected at all times.
- *Trust*, which implies that human respondents will not be respondent to any acts of deception or betrayal in the research process or its published outcomes.

Signature

31/10/2017
Date

Faculty of Education
Fakulteit Opvoedkunde
Lefapha la Thuto

A3 – Permission from Head of the Department (Hard copy & CD)

Permission form

I, [redacted] (your name only), Head of the Department of [redacted], at [redacted] agree to the research project titled, *The cognitive role of mock-ups in novice industrial designers' hierarchical thinking process*, be conducted in the Department.

I hereby give permission for eight third year Industrial Design students to be video recorded and observed for approximately six hours at the Pretoria Campus in the Industrial Design studio during the last week of January 2018 and the first week of February 2018.

I understand that the Industrial Design lecturers will not take part in this study, but will be asked to identify eight third year students that are top achievers in the subject Industrial Design II.

I understand that the researcher subscribes to the principles of:

- *Voluntary participation* in research, implying that the participants might withdraw from the research at any time.
- *Informed consent*, meaning that research participants must at all times be fully informed about the research process and purposes, and must give consent to their participation in the research.
- *Safety* in participation; put differently, the human respondents should not be paled at risk or harm of any kind.
- *Privacy*, meaning that the *confidentiality* and *anonymity* of human respondents should be protected at all times.
- *Trust*, which implies that human respondents will not be respondent to any acts of deception or betrayal in the research process or its published outcomes.

....
Signature

27/10/2017
....
Date

Faculty of Education
Fakulteit Opvoedkunde
Lefapha la Thuto

APPENDIX B – INFORMED CONSENT

B1 – Letter of invitation and informed consent (Hard copy & CD)

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
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LETTER OF PARTICIPANT INVITATION AND INFORMED CONSENT

Dear Student

I would like to invite you to participate in a research study that forms part of my M.Ed. (Masters) study in the Faculty of Education, University of Pretoria. This letter may help you to decide if you would like to participate. Before you agree to take part, you should fully understand what is involved.

WHAT IS THIS STUDY ALL ABOUT?

The purpose of this study is to explore and describe how graphic communication strategies used during the design process aid the design thinking process of Industrial Design students in their third year of study, when conceptualising and refining an idea when engaging in a given design project. Conducting research on the cognitive behaviour of Industrial Design students and how various graphic communication strategies might foster their design abilities, might enable me to understand how to improve Engineering Graphics and Design curricula and teaching strategies in schools and in teacher training departments. My study's aim is thus to provide guidance to the Engineering Graphics and Design curriculum developers to make provision for a more authentic view on the role of graphic communication in the design process.

WHAT ARE THE POTENTIAL BENEFITS THAT MAY COME FROM THE STUDY?

A potential benefit to you as participant is gaining self-awareness of your own design process as well as your own reasoning skills for solving socio-technological design problems. Your participation, which might result from this study, can also make a significant contribution towards a better understanding on how to improve education for Industrial Design students.

WHAT WILL BE REQUIRED OF YOU IN THE STUDY?

If you decide to take part in the study, I will observe your thinking process during the ideation and refinement stages of your design project while collaborating with one of your fellow students. Observations will be conducted over a period of five days during end of January and beginning of February 2018. The observations will be video-recorded at [redacted] in the Industrial Design studio between 8:30 and 14:30. Observations will only be conducted on particular days during your normal design project timetable, during the first semester of your third year of study. This has been pre-arranged with your lecturers in the department. You and three other students will be grouped in pairs and asked to participate in my study. Each group will be asked to verbalise their thoughts and make sketches and mock-ups to understand and find a possible solution to a given design problem. As researcher, I will not disrupt your normal thinking

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process. Your thinking process will be video recorded and transcribed for analytical purposes. Only my supervisor and I will have access to this data. However, you will be allowed to view it at any time you wish during my research process. I will also need to have access to your written 'notes' and sketches made prior to the video recordings, in order to make sense of your sketches and mock-ups made during the recordings.

CAN ANY OF THE STUDY PROCEDURES RESULT IN PERSONAL RISK, DISCOMFORT OR INCONVENIENCE?

It is unlikely that you will be harmed, but you might feel awkward to think-aloud during the video recording. However, I will give you the opportunity to practice the technique prior to the video recording. You might also fear discovery of incompetence with regards to solving the design problem, but I want to assure you that I am not interested in assessing your performance and quality of your designed artefacts. I am interested in mapping your cognitive process involved while you are making conceptualisation sketches and constructing mock-ups.

WILL YOU RECEIVE ANY FINANCIAL COMPENSATION OR INCENTIVE FOR PARTICIPATING IN THE STUDY?

Please note that you will not get paid to participate in the study.

WHAT ARE YOUR RIGHTS AS A PARTICIPANT IN THIS STUDY?

Your participation in this study is entirely voluntary. You have the right to withdraw at any moment without any penalty or future disadvantage whatsoever. Your responsible lecturers at [redacted] will not discriminate against you should you decide not to participate in this study. In addition, please take note that your intellectual property, namely conceptualisation sketches and mock-ups, will be fully respected and acknowledged during and after the project.

HOW WILL CONFIDENTIALITY AND ANONYMITY BE ASSURED IN THE STUDY?

Your identity will be protected as far as possible. The information received during the project will only be used for research purposes. The information will not be released for any academic assessment, study progress and/or disciplinary purposes. Only my supervisor and I will know your real name, as a pseudonym will be used during data collection, transcription and reporting. Your university will not be identified either. I will appeal to your lecturers, fellow students and team member, to keep each other's identities confidential.

During the protocol sessions, which will be video recorded, it is impossible to keep your identities confidential at all times as your faces might appear in the video footage. However, strict assurances will be provided that under no circumstances will such video recordings be released for public consumption, including its use in research presentations at conferences or in any other research output. However, if there is need for me to include screenshots from the video footage as an attempt to provide emphasis in any of my research outputs, I will ensure that your faces will be excluded or blurred from the screenshot.

In my research dissertation and in any other academic communication, pseudonyms will be used and no other identifying information will be provided. Collected data will be in my or my supervisor's possession and will be locked up for safety and confidential purposes. After completion of the study, the material will be safely stored at the university's Science, Mathematics and Technology Education Department for fifteen years.

HAS THE STUDY RECEIVED ETHICAL APPROVAL?

Yes. The Research Ethics Committee of the University of Pretoria has approved the formal study proposal. In addition, the Research Ethics Committee of the [redacted] has granted written approval for the study. All parts of the study will be conducted according to internationally accepted ethical principles.

If you wish to enquire and/or lodge a complaint regarding the ethical aspects of the study, please feel free to contact the University of Pretoria, Faculty of Education Research Ethics Administration Officer, Ms. M Leask (edu.ethicsadmin@up.ac.za).

A FINAL WORD

Your co-operation and participation in the study is greatly appreciated. Please sign the underneath informed consent if you agree to participate in the study. In such a case, you will receive a copy of the signed informed consent from the researcher.

For any further queries, please do not hesitate to contact me or my supervisor at the contact details provided below.

Your support in this matter is much appreciated.

Mr. Stiaan Kamffer (researcher)
084 569 6827
stiaan.kamffer@up.ac.za

Dr. Grietjie Haupt (supervisor)
(012) 420 5631
grietjie.haupt@up.ac.za

B2 – Student consent forms (Hard copy & CD)

Participant 1

Acceptance of Invitation and Informed Consent

I hereby confirm that I have been adequately informed by the researcher about the nature, conduct, benefits and risks of the proposed study. I have also received, read and understood the necessary written information. I am aware that the results of the study will be anonymously processed into a research report. I accept the fact that my fellow students will be aware of my participation in this project. I understand that my participation is voluntary and that I may, at any moment, without prejudice, withdraw my consent and participation in the study. I acknowledge that I had sufficient opportunity to ask any questions about the research. I hereby declare that I agree to participate in this research out of my own free will.

Participant's full names: [redacted] (Print please)

Participant's surname: [redacted]

Contact number of participant: [redacted]

E-mail address of participant: [redacted]

Date: 2017/10/30

Participant's signature:

Participant 2

Acceptance of Invitation and Informed Consent

I hereby confirm that I have been adequately informed by the researcher about the nature, conduct, benefits and risks of the proposed study. I have also received, read and understood the necessary written information. I am aware that the results of the study will be anonymously processed into a research report. I accept the fact that my fellow students will be aware of my participation in this project. I understand that my participation is voluntary and that I may, at any moment, without prejudice, withdraw my consent and participation in the study. I acknowledge that I had sufficient opportunity to ask any questions about the research. I hereby declare that I agree to participate in this research out of my own free will.

Participant's full names: [redacted] (Print please)

Participant's surname: [redacted]

Contact number of participant: [redacted]

E-mail address of participant: [redacted]

Date: 30/10/2017

Participant's signature:

Participant 3

Acceptance of Invitation and Informed Consent

I hereby confirm that I have been adequately informed by the researcher about the nature, conduct, benefits and risks of the proposed study. I have also received, read and understood the necessary written information. I am aware that the results of the study will be anonymously processed into a research report. I accept the fact that my fellow students will be aware of my participation in this project. I understand that my participation is voluntary and that I may, at any moment, without prejudice, withdraw my consent and participation in the study. I acknowledge that I had sufficient opportunity to ask any questions about the research. I hereby declare that I agree to participate in this research out of my own free will.

Participant's full names: [redacted] (Print please)

Participant's surname: [redacted]

Contact number of participant: [redacted]

E-mail address of participant: [redacted]

Date: 2017-10-30

Participant's signature: [redacted]

Participant 4

Acceptance of Invitation and Informed Consent

I hereby confirm that I have been adequately informed by the researcher about the nature, conduct, benefits and risks of the proposed study. I have also received, read and understood the necessary written information. I am aware that the results of the study will be anonymously processed into a research report. I accept the fact that my fellow students will be aware of my participation in this project. I understand that my participation is voluntary and that I may, at any moment, without prejudice, withdraw my consent and participation in the study. I acknowledge that I had sufficient opportunity to ask any questions about the research. I hereby declare that I agree to participate in this research out of my own free will.

Participant's full names: [redacted] (Print please)

Participant's surname: [redacted]

Contact number of participant: [redacted]

E-mail address of participant: [redacted]

Date: 30/10/2017

Participant's signature:

B3 – Lecturer confidentiality agreement (Hard copy & CD)

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LECTURER CONFIDENTIALITY AGREEMENT

Study: The cognitive role of mock-ups in novice industrial designers' hierarchical thinking process.

I, [redacted] (name of lecturer), agree to assist ***Christiaan Johannes Kamffer*** (name of primary investigator), with the sample selection process of this study.

I agree that I will:

- keep all academic performance information of the participants and non-participants confidential and not discuss or share the information in any form or format (e.g. disks, hard-copy document) with anyone other than the primary investigator of this study; and
- keep all discussions regarding the selection process of this study confidential and not discuss or share the information in any form or format (e.g. disks, hard-copy document) with anyone other than the primary investigator of this study.

Signature of the lecturer	29/1/2018 **Date**
Signature of the researcher	29/1/18 **Date**
Signature of the supervisor	5/02/2018 **Date**

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LECTURER CONFIDENTIALITY AGREEMENT

Study: The cognitive role of mock-ups in novice industrial designers' hierarchical thinking process.

I, [redacted] (name of lecturer), agree to assist ***Christiaan Johannes Kamffer*** (name of primary investigator), with the sample selection process of this study.

I agree that I will:

- keep all academic performance information of the participants and non-participants confidential and not discuss or share the information in any form or format (e.g. disks, hard-copy document) with anyone other than the primary investigator of this study; and
- keep all discussions regarding the selection process of this study confidential and not discuss or share the information in any form or format (e.g. disks, hard-copy document) with anyone other than the primary investigator of this study.

.... **Signature of the lecturer**	29/1/2018 .... **Date**
.... **Signature of the researcher**	29/01/2018 .... **Date**
.... **Signature of the supervisor**	5/02/2018 .... **Date**

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B4 – Camera technician confidentiality agreement (Hard copy & CD)

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CAMERA TECHNICIAN CONFIDENTIALITY AGREEMENT

Study: The cognitive role of mock-ups in novice industrial designers' hierarchical thinking process.

I, [redacted] (name of research assistant), agree to assist ***Christiaan Johannes Kamffer*** (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	29 January 2018 **Date**
Signature of the researcher	29/01/18 **Date**
Signature of the supervisor	5/02/2018 **Date**

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APPENDIX C – DATA GENERATION INSTRUMENT

C1 – The design task (Hard copy & CD)

DESIGN BRIEF

Dear students,

This project is a group project where you are required to work in a small team made up of your fellow class members. As a young industrial designer, it is important to develop your skills of being an effective team member. You are required to make a significant contribution to the design project your team is tasked with. Assessing your contribution in this group project is how you will receive a mark at the end of the project. The ability to demonstrate your competence as an effective team member is an exit level requirement for this qualification. Therefore, it is important that you use this project to prove your competence as it is one of the two formal third year project where this competency is evaluated. The National Higher Qualification Framework of South Africa expect this competence as one of the requirements before graduating:

> **Accountability:** Demonstrate an ability to work effectively in a team or group, and to take responsibility for his or her decisions and actions and the decisions and actions of others within well-defined contexts, including the responsibility for the use of resources where appropriate.

This project is delivered in the block project mode which means:

- Each day has a deliverable that must be submitted by the whole team at which time you will have a meeting with the lecturer to discuss your submission.
- You must be in the studio every day for the duration of the block project (from 8:30 until completion of daily deliverable).
- In each deliverable it must be clearly indicated what each team members contribution to that days deliverable was.
- No other classes will run during the block project.

1

STANDARD INSTRUCTIONS

1. Any work handed in or set up late for a deadline will not be evaluated and will receive a zero.
2. Any project work that is submitted which is not to the standard set by the brief will not be evaluated.
3. Attendance is compulsory at the following project events.
    - Project briefing
    - Output deadlines
    - Project activities
    - Group critique sessions
    - Individual critique sessions
4. Arriving late for any project event will result in the lecturer excluding you from the event. The lecturer will not brief you or give you any information or documentation you have to find your own way getting the necessary information or copies of documentation.
5. No cell phone usage during project events.
6. One on one project related meetings with the lecture may only take place during the time periods set out on your timetable for this subject.
7. Timing and appointment for one on one project related meetings must be set in advance with the relevant lecturer.
8. Student will be responsible throughout projects for the safe storage of their own work in progress and completed project work.
9. All projects must be supported by a signed statement prepared by the student that clearly states that the work presented by the student is the result of his/her own endeavours and is to the best of their knowledge original.

If it can be seen that through collaboration, accident or deliberate intent a student has adopted a specific idea from a colleague or any alternative source and has incorporated this idea into his / her design thinking. It is the responsibility of the student to acknowledge the source.

PROBLEM STATEMENT

Design a cost effective alternative to Nespresso pods

In this project your team is required to design and develop a hand held or counter top machine that converts aluminium foil sheet into foil pods. The user must be able to fill these foil pods with ground coffee and seal the pods ready for use. Your simple machine (hand-held or counter-top) must:

1. Cut foil blanks;
2. Form foil blanks into pods with a lip;
3. Seal the lid blanks onto the pod lip once filled with ground coffee.

This new product is intended to give coffee lovers a new alternative way to create barrister style coffee in a more cost effective manner than other solutions, while using existing coffee making machines. The inexpensive foil container is intended for a single use and your machine can be used to create new pods from store bought heavy gauge aluminium foil sheet.

DESIGN TASK

Each team member must contribute to the research by investigating one aspect of the machines function. Each team member must presented their research using free hand ideation sketches and digital images and schematics collected from various sources. Each team member is required to produce one page of ideation sketches and two pages of digital images that summaries their research topic. Your work must be clearly labelled on each page with your name, date and the task you completed for the team. All pages must be printed and presented to the lecturer at the daily deadline meeting.

- Determine through research effective hand operated methods to cut blanks out of aluminium foil sheet.
- Determine through research effective hand operated methods to form a single lipped aluminium pod from the blank cut outs.
- Determine through research effective hand operated methods to seal the lid blank to the rim of the pod.

All work must be presented by the whole team to the lecturer for discussion.

Final meeting time: 14:30

APPENDIX D – EXAMPLES OF VISUAL DATA

D1 – Photographs of the original sketches and written notes (CD only)

APPENDIX E – DATA ANALYSIS PROCEDURES

E1 – Code book (Hard copy & CD)

Aspectual intentions and themes

Aspectual intentions	Aspectual intention themes
Economic aspect	Cost effectiveness
	Recyclability
Ethical aspect	Safety
Formative aspect	Clamping
	Compressing
	Cutting
	Folding
	Forming
	Sealing
Kinematic aspect	Contracting
	Expanding
	Rolling
	Rotating
Physical aspect	Material
Quantitative aspect	Tolerance
Sensitive aspect	Sensory
Spatial aspect	Shape
	Size
	Texture

Functional intentions

Functional intentions	
Blank cutting: Blade cutting	Pod forming: Compress forming
Blank cutting: Clamping shut	Pod forming: Ease-of-use
Blank cutting: Cutting plate	Pod forming: Foil folds on lines
Blank cutting: Dispensing	Pod forming: Pressing
Blank cutting: Fall through after cutting	Pod forming: Shear pressing
Blank cutting: Guide for cutting	Pod forming: Slip allowance
Blank cutting: Handheld	Pod forming: Use coffee for compressing
Blank cutting: Laser cutting	Pod forming: Vacuum forming
Blank cutting: Pod and lid as one piece of foil	Reuse lid
Blank cutting: Pressing	Sealing: Clamp sealing
Blank cutting: Punching	Sealing: Folding lid over pod lip
Blank cutting: Releasing blank	Sealing: Hand sealing
Blank cutting: Rolling	Sealing: Mechanical sealing
Blank cutting: Rolling disc	Sealing: Melt pressing
Blank cutting: Rotation cutting	Sealing: Pressing
Blank cutting: Running rotating blade	Sealing: Punch pressing
Blank cutting: Scoop cutting	Sealing: Ring pressing

Blank cutting: Vacuum cut	Sealing: Rolling
Gripping	Sealing: Rotating press
Lip forming: Folding foil to make lip	Sliding
Lip forming: Pressing	

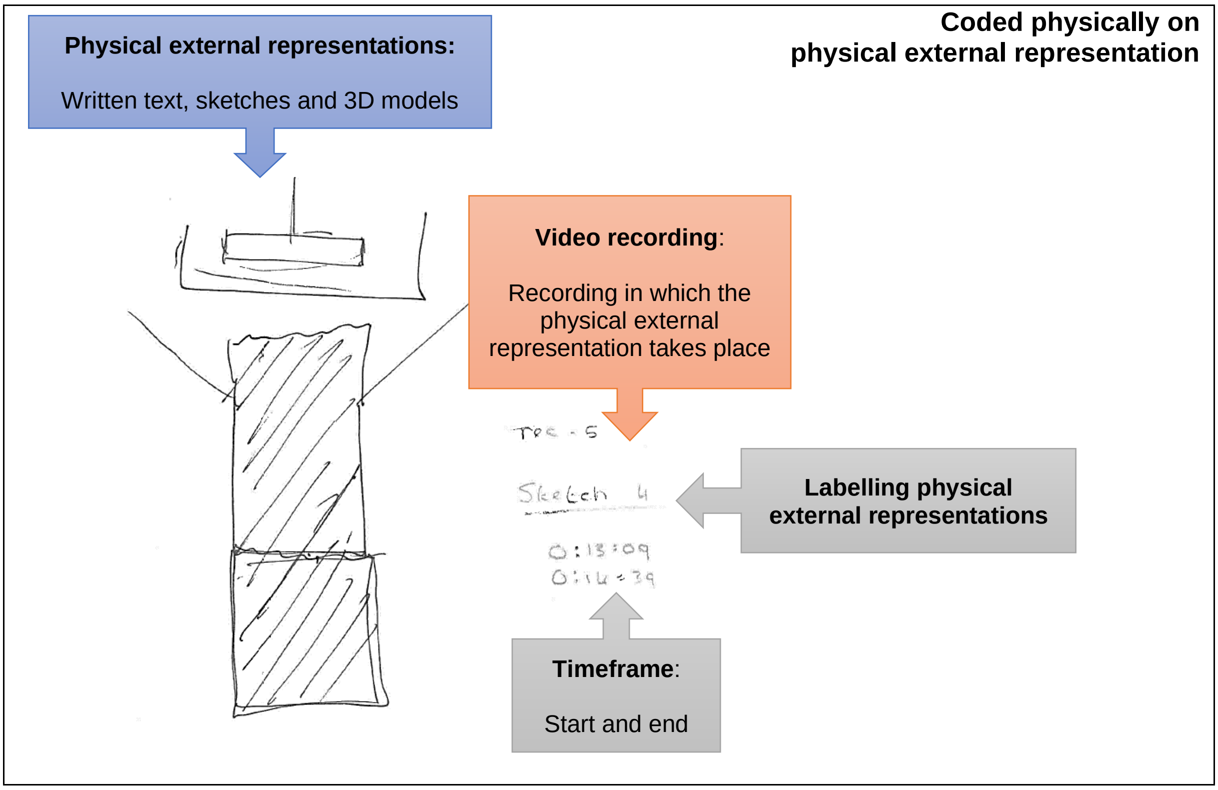
Physical elements

Physical elements	
Air-tight	Lip rolled over the edge
Blade: Circular	Lip rolled over to form the edge
Blade: Holes for ventilation	Lock foil sheet in place
Blade: Rolling	Male die
Blade: Serrated (teeth) cutting edge	Male mould
Channel	Mechanical press
Circular disc	Minimal tolerance
Clamp	Pin releasing blank
Coffee	Pinching
Coffee takes the form of the pod	Pizza cutter
Compressing die	Plated
Convex shape	Pod blank
Cutting edge(s)	Pod shape when sealed
Fan when pressed	Press tool (rod) pressing down
Female mould	Puncture
Foil dispenser	Puncture creates flange
Foil sheet	Roller(s)
Fold lid over pod lip by hand	Rotate over pod to seal
Folding lid over lip edge	Rounded edges
Folding lines	Rubber
Forming foil around existing artefact	Scissor
Forming gel / silicon	Seal with fingers
Funnel	Seal: O-ring
G-clamp	Shaft
Glue present on existing artefact	Shape of actual pod (existing artefact)
Groove	Size of lid blank
Hand form the pod before pressing in male die	Size of the pod blank
Handle	Smooth surface
Hinge	Spindle with blade
Hole	Taper point at the bottom
Hole punch (U-shaped)	Taper shape
Hollow	Tide pod
Hook shape	Tin opener
Ice-cream scoop	Tolerance size of pod blank
Indent	Tongs
Laser cutting platform	Triangular die
Lid attached to foil pod blank	Twist
Lid blank	Vacuum machine
Lid flange	Vacuum to form the pod over mould
Lip on the edge of the pod	Wheel(s)

Implementation intentions
Allow foil to be pressed into a mould
Change approach: Combining the pod and lid blanks will not work
Change approach: Does not work effectively
Change approach: No need for a clamp
Change approach: Too complex
Change approach: Use hook shape rather than rounded edges to fold lid over lip
Combining the different stages of the artefact
Draw a line where the pod lip ends to get the size of the blank
Get user involved in making pod
Glue is a health hazard
Immediate shear results in pod being too small
Increase pod blank size to incorporate lip
Prevent foil from tearing
Shear is good for cutting blanks
Use as footprint
Use coffee to compress and form foil pod
Use press cutting instead of roll cutting
Use press cutting instead of rotation cutting

E2 – Coding procedures (Hard copy & CD)

Macro analysis: sub-level 1 – Code timeframe



Coded using Microsoft Excel

Timeframe:

Start and end time of each physical external representation

Physical external representations:

Written text, sketches and 3D models

TIMEFRAME		Physical external representation
Start	**End**	
Stage 1 - T1_P2 was responsible for the PER of Day_1		
00:55:39	00:58:49	Sketch 1A
00:56:14	00:57:39	Sketch 1B
01:00:18	01:00:42	Sketch 2A
01:02:21	01:02:58	Sketch 2B
01:14:59	01:15:48	Annotation - Sketch 2A+B
01:16:21	01:17:15	Annotation - Sketch 1A+B
01:48:22	01:51:31	Sketch 3
01:51:34	02:51:53	Annotation - Sketch 3

Ordering:

Organised according to the participant responsible for particular artefact stage in ascending (time) format

Macro analysis: sub-level 2 – Identify events and provide an overview

Coded using Microsoft Excel

Timeframe:

Start and end

Physical external representations:

Written text, sketches and 3D models

Participant and Stage:

Participant responsible for particular artefact stage

Overview:

General overview of what occurred during the timeframe of particular events

Time	Participant	Stage	Physical external representation	Overview
0:55:39 - 0:58:49	T1_P2	Stage 2	Sketch 1A	**Die forming (female)** Thinking of a male and female mould for die forming the foil into a pod. Speaking about pressing the male and female into one another, which will give the shape of the pod.
0:56:14 - 0:57:39	T1_P2	Stage 2	Sketch 1B	**Die forming (male)** Thinking of a male and female mould for die forming the foil into a pod. Speaking about pressing the male and female into one another, which will give the shape of the pod.

Ordering:

Organised according to time in ascending format

Meso analysis: sub-level 3 – Identify significant events and then code episodes and segments from the significant events

Coded using Microsoft Excel

Episodes and segments:

Significant events coded as episodes, which consist of segments

Participant:

Participant captured during significant events

Episodes	Segments	Time	Participant	Stage	Physical external representation
1	**1**	0:55:39 - 0:58:49	T1_P2	Stage 2	Sketch 1A
1	**2**	0:56:14 - 0:57:39	T1_P2	Stage 2	Sketch 1B
2	**1**	1:00:18 - 1:00:42	T1_P2	Stage 2	Sketch 2A
2	**2**	1:02:21 - 1:02:58	T1_P2	Stage 2	Sketch 2B
3	**1**	1:27:16 - 1:46:29	T1_P1	Stage 1	Sketch 3
4	**1**	1:32:45 - 1:40:13	T1_P2	Stage 3	Sketch 4
5	**1**	1:35:14 - 1:41:09	T1_P2	Stage 3	Sketch 5A
5	**2**	1:41:11 - 1:42:00	T1_P2	Stage 3	Sketch 5B
5	**3**	1:43:35 - 1:44:25	T1_P2	Stage 3	Sketch 5C
6	**1**	1:46:38 - 1:49:14	T1_P1	Stage 1	Sketch 6

Ordering:

Organised according to time in ascending format

Coded using ATLAS.ti

Episodes and segments:

Coded episodes and segments

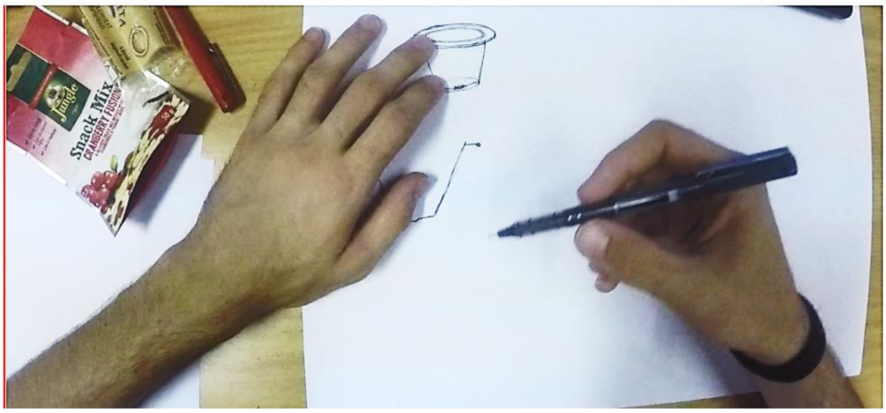
Video recording (document):

Recording in which the particular episodes and segments are shown

Name	Document
T2_D1_E11_S2	T2_P4_D1 - Recording 6
T2_D1_E12_S1	T2_P4_D1 - Recording 7
T2_D1_E13_S1	T2_P3_D1 - Recording 7
T2_D1_E14_S1	T2_P3_D1 - Recording 8
T2_D1_E15_S1	T2_P4_D1 - Recording 10
T2_D1_E15_S2	T2_P4_D1 - Recording 10

Physical external representations:

Written text, sketches and 3D models



Edited 2018/09/21 08:05 by Stiaan

Sketch 15

3:13:47 - 3:14:39

Timeframe:

Start and end

Micro analysis: sub-level 4 – Code a priori hierarchical thinking levels

Coded using ATLAS.ti

Video recording:

Recording showing what the participant is doing during coded instances

Timeframe:

Coded start and end time of each instance

Hierarchical thinking levels:

Levels coded in colour – yellow (aspectual intention themes), blue (functional intentions), green (physical elements) and purple (implementation intentions)

Coded using Microsoft Excel

Intentions:

Coded intentions, in this case aspectual intentions with its relevant themes

Occurrences:

Number of occurrences took place (overall and per team) per code during the whole preliminary design phase

		Occurrences			
Aspectual intentions	**Aspectual intention themes**	**Overall**		**Team 1**	**Team 2**
Formative aspect	Clamping	125	7	4	3
	Compressing		17	6	11
	Cutting		29	23	6
	Folding		7	2	5
	Forming		29	7	22
	Sealing		36	13	23
		238		**118**	**120**

Totals:

Total occurrences of codes overall and per team

Coded using Microsoft Excel

Occurrences:

Number of occurrences took place (overall and per team) per code during the whole preliminary design phase

Intentions:

Coded aspectual intentions with its relevant themes

Occurrences of links

Functional intentions	Physical elements	Overall	Team 1	Team 2
Blank cutting: Blade cutting	Blade: Circular	1	1	0
	Blade: Serrated (teeth) cutting edge	3	3	0
	Cutting edge(s)	1	0	1
	Hollow	1	1	0
	Total links = 76	**83**	**40**	**43**

Total links:

Total amount of links made with other intentions

Totals:

Total occurrences of codes overall and per team

Micro analysis: sub-level 5 – Code a priori idea transformations

Coded using ATLAS.ti

Video recording:

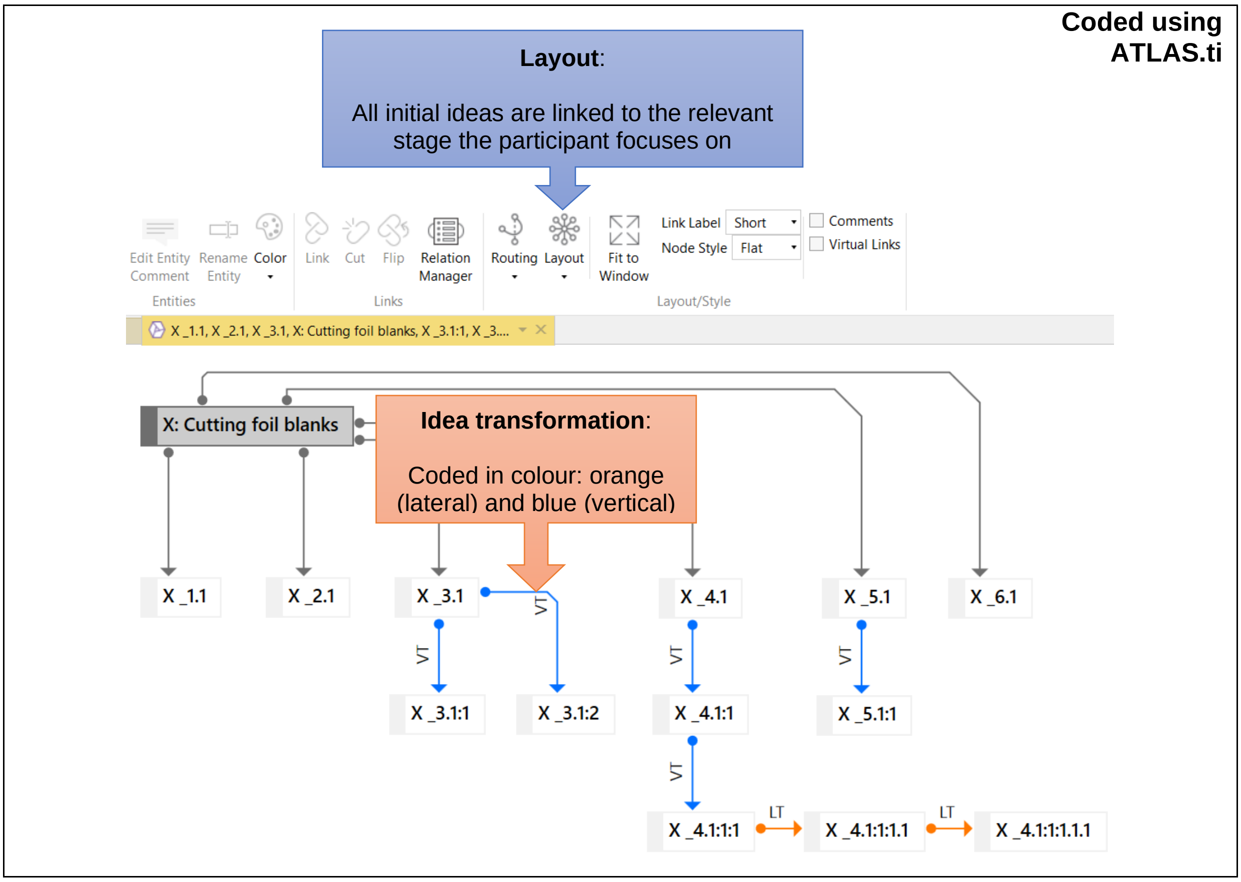
Recording showing what the participant is doing during coded instances

Timeframe:

Coded start and end time of each instance

Idea transformation:

Initial and transformed ideas are coded in white



E3 – Macro analysis: sub-level 1 (CD only)

E4 – Macro analysis: sub-level 2 (CD only)

E5 – Meso analysis: sub-level 3 (CD only)

E6 – Micro analysis: sub-level 4 (CD only)

E7 – Micro analysis: sub-level 5 (CD only)

APPENDIX F – POLICY DOCUMENTS

F1 – CAPS document for EGD (CD only)

F2 – PAT document for EGD (CD only)

APPENDIX G – DOOYEWEERD'S THEORY OF MODAL ASPECTS

G1 – Summary of Dooyeweerd's aspects of temporal reality (Hard copy & CD)

In Dooyeweerd's theory of aspectual modalities of reality, he lists fifteen aspects for identifying abstractions (Basden, 2011). Based on The Dooyeweerd Pages website (Basden, 2000), I briefly summarise each of these aspects accompanied with an example.

Dooyeweerd's fifteen aspects of temporal reality summarised with an example

Aspect	Meaning	Example: Newspaper
Aesthetic	Harmony that brings delight and enjoyment.	Is the articles in a newspaper interesting? Does it give you information about what is happening?
Analytical	Distinction and conceptualisation if something is meaningful.	Can you distinguish things in a newspaper, and think about them?
Biotic	Live functions: the action of organisms in an environment.	Certain nerve cells in your brain are activated when reading a newspaper.
Economic	The frugal management of resources.	Are journalists able to write articles that fit in provided columns.
Ethical	Self-giving love, wellbeing and safety.	Does an article go beyond doing justice?
Formative	The deliberate shaping of things: achievement, construction, history and technology.	The impression you construct on the current state of affairs reported in a newspaper.
Juridical	Appropriateness referring to the responsibility of enforcement, law and policy.	Does an article in a newspaper do a story justice?
Kinematic	Movement: ongoing and continuous movement of things.	A newspaper invites you to gaze upon it and turn the pages.
Lingual	Meaning carried by symbold: the expression, recording and interpretation of something.	Do you understand what is reported in a newspaper.
Physical	Forces, energy and matter of things.	A newspaper is light in weight and produces light and heat when burnt.
Pistic	Vision and aspiration that motivates commitment leading to certainty and belief.	What you believe in what you are reading in an article.

Quantitative	Discrete amount: numbers and order of quantities.	A newspaper consists of a number of pages.
Sensitive	Sense, feeling and emotion: interactive engagement with the world.	You can see and touch a newspaper.
Social	Submerging in social interaction: relationships, roles and convention.	You have a role as reader.
Spatial	Continuous space: extension of the surrounding space.	A newspaper is laid out in rectangular pages folded in half.