CRANFIELD UNIVERSITY

Konstantinos Kentrotis

Using design theory to bridge Design and Science: understanding innovation and the role of Design when developing novel technologies

School of Water, Energy and Environment (SWEE)
Centre for Competitive Creative Design

PhD
Academic Year: 2016 - 2019

Supervisor: Professor Leon Williams
Associate Supervisor: Dr Ewan McAdam
March 2019

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ABSTRACT

The value of design is nowadays largely recognised, especially in its manifestations of design thinking, product and service design, business organisation as well as disruptive innovation. Design in the context of the present study is examined from a different perspective, the one of modern design theory. It is treated as a human activity of generating innovative concepts, regardless of fields of disciplines, in an attempt to identify which are the techniques that enable invention to occur. The study aims at providing a better understanding of design and its cognitive processes, relying on formal design theory and using a real-world design challenge as a case study.

The case study corresponds to a global, high-profile project funded by the Bill & Melinda Gates Foundation. Contemporary western-style toilets require a large quantity of clean water and an integrated sewage system to operate, but 2.3 billion people remain without access to improved sanitation. For this part of the globe's population, a waterless and energy-neutral toilet would constitute a solution with high potential. An important piece of this toilet is a technology which dewaters and dries human faeces so that it can be further processed by the system. At the moment, such a technology with low requirements in terms of size, energy and power demands does not exist. In the context of this research, a novel, patented drying technology was designed and developed.

The novel dryer designed and developed in the context of the aforementioned project is represented by using modern design theory. The case study is also used to demonstrate the way that innovative concepts are generated and to identify the design techniques that are crucial to invention process, irrelevant to the field or discipline within which it takes place.

Keywords: *axiomatic design, design theory, drying technology, design process, case study, C-K theory, generativity, innovation, innovative conceptual design*

ACKNOWLEDGEMENTS

I arrived in Cranfield University's Centre for Creative Competitive Design (C4D) in October 2014, seeking to learn about Design and Innovation. Back then, it was impossible for me to think that this would be the topic of my Ph.D. research. It was also impossible to imagine that I would have the privilege to see C4D grow into a Design Centre of the status and importance that it has nowadays.

First and foremost, I would like to thank my supervisor Dr Matt Collins. I first met Matt when he was finishing his Ph.D. in Breakthrough Innovation. He gave a one-day lecture in Technology & Prototyping and I can still remember that day vividly as one of the best lectures I ever had. I am always impressed by his ability to convey his 25-year experience as an industrial designer and inventor in such a simple way. I am indebted to Matt for mentoring me through my Ph.D. journey, for everything that he taught me and for teaching me how to appreciate simplicity. His constant support and presence made my Ph.D. journey as enjoyable and constructive as possible.

Moreover, I would like to thank Prof Leon Williams for his guidance and supervision for the last few months of my Ph.D. It is thanks to Leon that I learned, when I was still a master's student, how to organise, plan, report and present at the highest possible standards. His faith and trust in me all these years have been crucial to the successful completion of my research journey.

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Thank you to the Bill & Melinda Gates Foundation for generously funding my Ph.D. research and for giving me the opportunity to work on their 'reinvent the toilet' project. I hope that my work and commitment to the project has met some of their expectations.

Last but not least, I am grateful to Christina for her presence in my life, her companionship and support in every step I made in the past 12 years of my career. I have no other way to thank her but to dedicate this dissertation to her.

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LIST OF ABBREVIATIONS

AD	Axiomatic Design
BMGates	Bill & Melinda Gates
CAs	Customer Attributes
C→C	Concept to Concept
CDP	Coupled Design Process
C-K	Concepts-Knowledge
C→K/Ma	Concepts-Knowledge/Matroid model
CURES	Cranfield's University' s Research Ethics Working Committee
C4D	Centre for Competitive Creative Design
DFA	Deterministic Finite Automaton
DPs	Design Parameters
e.g.	example
FBS	Function-Behaviour-Structure
FRs	Functional Requirements
GDT	General Design Theory
ID	Infused Design
i.e.	that is
K→C	Knowledge to Concept
K→K	Knowledge to Knowledge
LEV	Local Exhaust Ventilation
lpm	litres per minute
mc	Moisture content
NP-hard	Non-Polynomial hard
PhD	Philosophy Doctorate
PID	Proportional-Integral-Derivative
PRISMA	Preferred Reporting Items of Systematic Literature Review
PVs	Process Variables
Res Eng Des	Research in Engineering Design
RQ	Research Question
R&D	Research & Development
TRL	Technology Readiness Level

UNDESA	United Nations Department of Economic and Social Affairs
VDI	Verein Deutscher Ingenieure
VIP	Ventilated Improved Pit
wb	Water basis
WHO	Water Health Organisation
wt% mc	moisture content, water basis

1 INTRODUCTION

"Everything must have a beginning to speak in a Sanchean phrase; […] Invention, it must be humbly admitted, does not consist in creating out of void, but out of chaos; the materials must, in the first place, be afforded".

- Mary Shelley, *Frankenstein; or, the Modern Prometheus* (1818)

This chapter sets out the personal and academic motivations for undertaking this research and states the study's aim and objectives. Finally, section 1.3 explains the structure of the dissertation.

Keywords for this chapter: *introductory remarks, motivations, aim and objectives, dissertation organisation*

1.1 Study motivations

There have been many cases in the history of science that people have been acknowledged for their unconventional way of thinking and their creative problem-solving skills. For example, we can refer to Kekulé's dream of the benzene ring (Rudofsky and Wotiz 1988), Watt's and Bolton's double acting steam engine (Scherer 1965), Einstein's visual thinking which led to the general theory of relativity (Gross 2005) and Feynman who got inspired to create his famous diagrams by a wobbling plate with a Cornell logo on (Kaiser 2005).

What is similar in all these cases? –Invention: this 'creative leap' needed to provide a solution to a problem, which to the majority of peers seems impossible to think of. This work is motivated by the desire to explain such creative leaps and the process of innovation in general. Over the past four years that he has been working in Cranfield University's Centre for Competitive Creative Design (C4D), the author has identified a series of elements that are crucial to innovation. These include, among others, imagination, resilience, persistence, the ability to understand the deeper cause of a problem, curiosity to conduct research and decent ability to grasp the significance and applicability of a technology. However, when reviewing past cases of inventors and innovators, none of these elements seemed to be enough to answer the question: 'what makes us inventors'? Is there a systematic way of inventing? Is it a matter of a particular

way of thinking, technique or methodology? Is the ability to invent inherent or not? These were questions that intrigued the author and motivated him to begin a PhD in this field. His intuition was telling him that studying Design in more depth would lead to the right answers.

However, and for reasons of clarity, it has to be declared that the ability to invent or to innovate was never seen by the author as an exclusive privilege or skill of designers. There was just a feeling that whatever this skill was, it appears more often -and hence it is easier to be identified and explained- in the context of design discipline. Hence, the initial goal was to identify this ability through design research, to isolate it and then examine whether it can be transferred and exploited in other disciplines, including science.

But such an attempt to bridge the two disciplines is not easy at all. It is a common belief that design and science are fundamentally different (Giaccardi and Fischer 2008) and there are many views from the literature on the differences and commonalities between the two disciplines. Willem (1990) implies that design is concerned with all human-made objects. Similarly, Cross (1993) describes science as the discipline which "studies the natural world" and design as the one studying "the man-made world". Simon (1996) established the view that design is conceived as the field that examines "how things ought to be" and science as the one that studies "how things are". Buchanan (1992a) argues that design is about conceiving or planning what does not yet exist, whilst science is about understanding the universal properties of whatever already exists. Skolimowski (1966) describes design (namely 'technology') as the discipline that creates reality according to human design and science as the field that investigates the given reality. Similar to this approach, Heylighen et al. (2009), based on Searle's (2001) theory of the 'direction of fit', parallelised design with the 'world to mind fit' and science with the 'mind to world fit'. In other words, design attempts to fit the designed artefact to the world whilst science attempts to fit the truth of the world into the human mind. Galle and Kroes (2014) claim that design and science aim at different things: the first aims at the production of artefact proposals and the latter at the production of theoretical knowledge.

The scope, stature and resources of the present study though, were ideal to attempt to bridge design and science. The 'reinvent the toilet project' constitutes a high-stature,

global project, requiring innovative thinking, involving a large number of researchers coming from multiple academic backgrounds and forming a complex problem environment. For this reason, this project was considered as ideal for this ambitious and challenging research question to be addressed.

The goal of the project is to develop a home-scale toilet which:

- Removes germs from human waste and recovers valuable resources such as energy, clean water, and nutrients
- Operates "off the grid" without connections to water, sewer, or electrical lines
- Costs less than $0.05 cents per user per day
- Promotes sustainable and financially profitable sanitation services and businesses that operate in poor, urban settings
- Is a truly aspirational next-generation product that everyone will want to use—in developed as well as developing nations

The toilet designed at Cranfield University, called 'the Nano Membrane Toilet' will be able to treat human waste on-site without external energy or water. It is designed for single-household use (equivalent to 10 people) and will accept urine and faeces as a mixture.

The present study concerns the separation of solids (faeces) both from unbound and loosely bound water (mostly urine) in the toilet, before the residual solids get transported into a combustor which will convert them into ash and energy. This separation is achieved via a drying device, referred to as 'dryer', the design and development of which is presented in this dissertation.

To date, the research presented in the context of the dissertation has resulted in:

- 1 successful, patented design (No. 7416662) (Appendix C)
- 1 published conference paper (Appendix F)
- 1 accepted journal paper (Appendix F)

1.2 Study aim and objectives

Aim:

- The aim of this study is to represent how the innovative concept of a drying device was generated as well as gather and share useful insights regarding the generation of innovative concepts and the bridging between design and science.

Objectives:

The individual objectives that have been addressed to deliver against the overall aim are to:

1. Conduct a systematic literature review to explore the research gap and opportunity space and define the research question

The first objective of the study is to conduct a literature review in the field of design theory, aiming to gather key findings that will help address the research question and to identify appropriate tools and methods to represent the design process of the newly-invented drying technology.

2. Use a case study to gather practical insights on the design of an innovative technology

The second objective is to represent the dryer's design process using appropriate tools identified from the literature research previously conducted. Since the dryer design was proven to be a successful one, this objective concerns the search for transferable knowledge and the gathering of insights deriving from the methodology and process followed to develop it.

3. Test and validate the novel technology developed in the context of the study

The dryer designed and developed in the context of the 'reinvent the toilet' project is validated by undertaking a series of tests. These tests assess the novel design in terms of the functional requirements set by the project scope.

4. Answer the research question by applying design theory

In the context of this objective, The dryer's design is evaluated using modern design theory. The analysis results are then used to address the research question.

5. Discuss results and key findings

Consolidate all findings and insight both form the case of the dryer development of the 'reinvent the toilet project' and the overall PhD journey. Cross-validate the study's key findings with those of other studies or the ones underpinned by existing theories. Emphasise new contribution to knowledge.

1.3 Research Methodology

1.3.1 Design method, methodology and process

Design method is defined as a consistent system of formal rules and instructions intended to guide the execution of a certain design activity from a given starting point to a desired final state (definition adaptated from Ernst Eder and Hosnedl 2007). Each method can be divided into more basic methods or to be combined with others into more comprehensive ones. A set of methods is called ***design methodology***. Thus, this term covers different sets of design methods corresponding to various fields of activities or branches of specialisation.

A methodology, which is tailored to the specific needs and requirements of each project, is related to a generic ***design process***, which describes a sequence of steps eventually leading to the desired result. In the case of (engineering) design, the desired result is usually an artefact that satisfies the functional and operational requirements as these were set at the specification phase. There are plenty of models -either descriptive or depictive- referring to the design process. Roozenburg and Cross (1991) proposed a taxonomy of design models of that time, using this separation as criterion. Some prominent examples of design process models have been developed by Archer (1984), Jones (1984) and by Pahl et al. (2007). Pahl et al.'s (2007) prescriptive model became particularly popular among the engineering design community. Hence, based on it, the German society of professional engineers (Verein Deutscher Ingenieure - VDI) produced a number of VDI Guidelines in this area, including VDI 2221: Systematic Approach to the Design of Technical Systems and Products (VDI 2221 1993). Although this model is in reality more extensive, it mainly consists of four phases:

Phase 1 Clarification of tasks: collection of information regarding the requirements to be embodied in the solution and also about the constraints.

Phase 2 Conceptual design: establishment of function structures; search for suitable solution principles; combination of the above into concept variants.

Phase 3 Embodiment design: having the concept as a reference, determination of the layout, formation and development of a technical product or system in accordance with relevant considerations.

Phase 4 Detailed design: arrangement of form, dimensions and surface properties of all the individual parts finally laid down; specification of materials; evaluation of technical and economic feasibility; production of drawings and other required documents. For the sake of simplicity, it can be considered that production planning is included in this phase.

These four phases might not necessarily include every possible procedure entailed in the design process, but they can be considered at an abstract level sufficient to describe it. If a simple deterministic finite automaton (DFA) were to be developed to depict the above process, it would probably look like the one in Figure 12. Each state represents one of the process phases and feedback provided at the end of each phase can be either positive '1', meaning that the result meets the requirements, or negative '0', meaning that another alternative has to be considered. At the end of state 4 ('detailed design'), the overall assessment leads to either the acceptance of the artefact as a working design ('1') or to its rejection ('0'), which in turn means that the whole process needs to be repeated.

State S_0: task clarification – starting state

State S_1: conceptual design

State S_2: embodiment design

State S_3: detailed design – end state

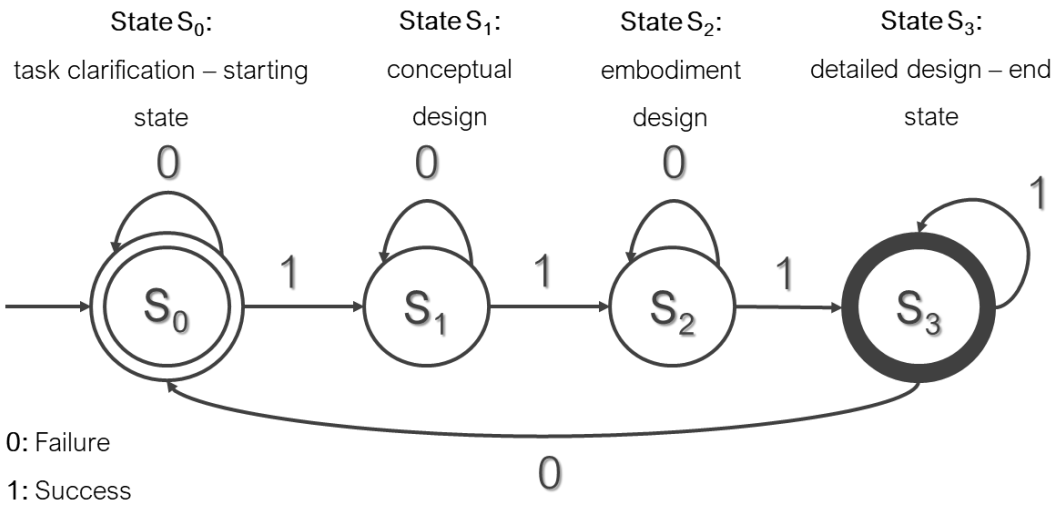

Figure 1. A deterministic finite automaton (DFA) depicting a simplistic version of a typical design process leading to an artefact proposition (Kentrotis 2019)

1.3.2 Common design methods

Although a complete list of design methods is almost impossible to be presented, as there are always revised and revisited methods appearing in the literature, the Table presented in Appendix A (Ernst and Hosnedl, 2007) summarises the most common methods, each one corresponding to a distinct stage of the design process (Note: the design stages referred to in Table 2, correspond to the ones of the automaton presented above).

The methods listed in the table above have been considered and several have been used throughout the execution of the study, as appropriate and as a part of an overall research methodology.

1.3.3 Developed methodology

A research methodology was developed in order to meet the demands of the study and the overall aim and objectives, as these are presented above. The methodology is presented in Figure 2. Letter ‘C’ is used as an abbreviation of ‘chapter’. The number following letter ‘c’ represents the corresponding number of each chapter. The way that the dissertation is broken into chapters is not randomly selected, as each chapter is linked to a distinct stage of the overall research methodology. The objectives met at each stage of the methodology are also included in the illustration. Each phase/chapter uses one or several of the methods mentioned in the table presented in Appendix A, in order to achieve its individual objective.

As a first step, a literature review was conducted to get an understanding of the design theory field, while a separate literature research was performed in the discipline of drying technology to gather the knowledge require to tackle the technical challenges set by the 'reinvent the toilet' project and more precisely, the dryer development. As a next step, a research methodology was developed and the design and development of a novel drying technology began, resulting to the novel design of the 'dryer'. The dryer was then tested and re-iterated twice based on the insights gained, until the final version resulted. The final dryer assessment and validation (which is presented in chapter 4)

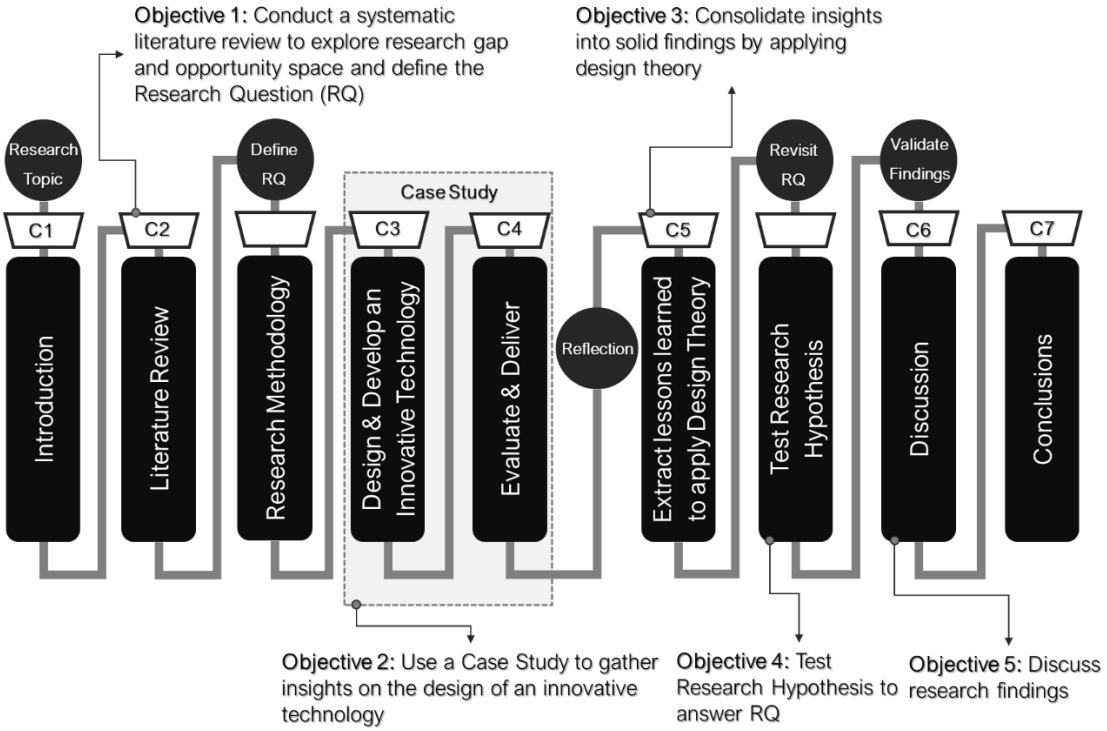

Figure 2. The developed research methodology

1.4 Organisation of the dissertation

The dissertation consists of eight chapters followed by appendices. A brief outline of each chapter and its content is described below:

Chapter 1 INTRODUCTION: Outlines the research motivations, aim and objectives. It presents the dissertation's organisation.

Chapter 2 LITERATURE REVIEW: Clarifies what design and design theory is and provides an overview of design theory. It presents a proposed method of systematic

literature review of the field, using a PRISMA (Preferred Reporting Items for Systematic Reviews) flow diagram. The goal of this chapter is to provide the reader with a) a better understanding of the theory behind the research topic and b) the theoretical platform required for the upcoming chapters of the dissertation.

Chapter 3 RESEARCH METHODOLOGY: Provides an overview of the most commonly used methods in design and layouts the overall methodology followed to perform the present research. Each individual stage of the methodology is linked to one of the objectives presented above.

Chapter 4 DESIGN AND DEVELOPMENT OF A NOVEL DRYING SYSTEM: Describes the design and development of a novel drying system for a waterless and energy-neutral toilet. The challenges of drying and the value of drying faeces are highlighted. After the scope and boundaries of the case study are reviewed, each stage of the design and development process is presented in detail.

Chapter 5 PERFORMANCE EVALUATION OF A NOVEL DRYING SYSTEM: Evaluates, through scientific testing, the novel drying system of which the conceptual design is described in chapter 4. The validation provided in this chapter renders the status of the designed concept as 'proven' and thus allows the discussion following thereon to be developed.

Chapter 6 EVALUATION OF A NOVEL TECHNOLOGY USING DESIGN THEORY: The designed system is analysed and assessed, this time from a design theory perspective to test the research hypothesis. This chapter attempts to identify the design technique that was prominent in the development of this novel technology and to answer the research question.

Chapter 7 DISCUSSION: Discusses the overall research methodology and reflects on the findings resulted from the study. It uses the latter in order to bridge design and science and to provide the final answer of how the two can be linked using design theory. The research limitations and the directions for further research are also presented.

Chapter 8 CONCLUSION: Summarises key learnings and consolidates overall research into tangible findings.

REFERENCES FOR EACH CHAPTER: Each chapter contains its own reference section, including journal papers, books and website references cited in this study. Hence, a separate chapter is not dedicated to references and/or bibliography.

APPENDICES: Contain additional information and evidence that support the research, which are either too extensive to be included in the main body of the dissertation or their inclusion might lead to dilution of the key message.

In case that time presses, it is recommended to read chapters 2, 3 and 5, before jumping to chapter 6, which reflects on the overall study and discusses the key findings and learnings. Figure 1 illustrates the prerequisite dependencies between individual chapters of the dissertation. Light grey arrows indicate a non-dependency between the chapters, whilst dark grey arrows mean that a prerequisite dependency exists. For example, the arrows from numbers 2 and 3 to number 5 indicate that they are prerequisites for reading chapter 6. On the contrary, chapters 2, 3 and 7 can be read independently of other chapters.

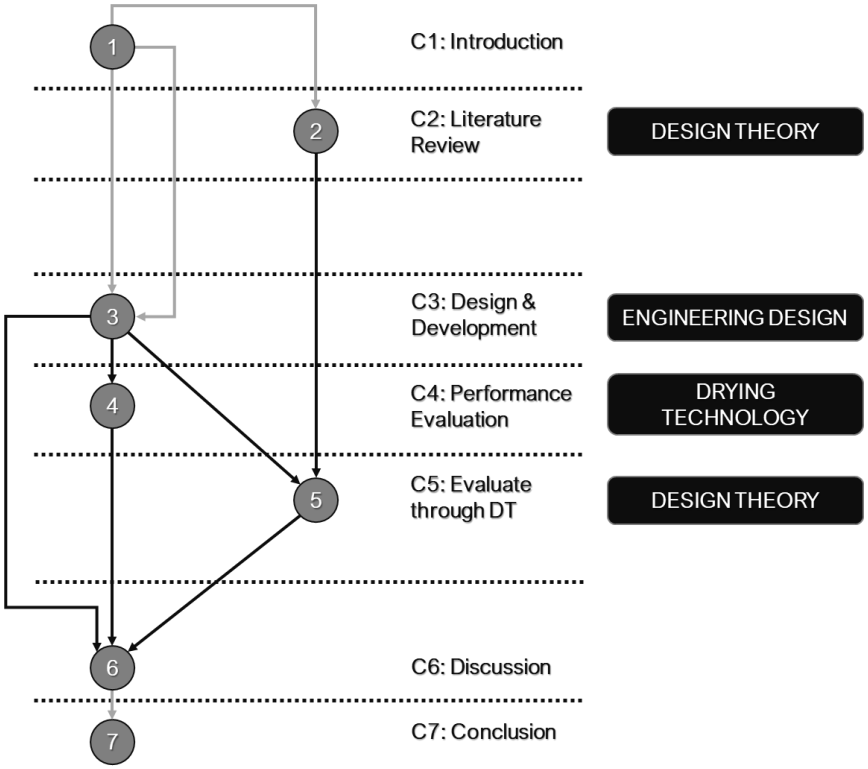

Figure 3. Prerequisite dependencies of the dissertation

1.5 Summary and next steps

In this chapter, the initial motivations, the aim and objectives for the study are stated and

a suitable methodology to address the research question is defined. In order to consolidate all these into a valid, solid research question, a review of relevant literature and key findings to date will be performed. The literature review that follows in chapter 2 fulfils this goal.

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2 LITERATURE REVIEW

Objective 1: conduct a literature review to explore the research gap and opportunity space and define the research question.

This chapter reviews the literature related to design theory and nourishes a discussion about design, complexity and innovation. It also reveals the challenges, the gap and opportunities of the present study, as well as how the research question began to emerge. The focus is put on two modern theories: axiomatic design (AD) and C-K theory. These theories were not randomly selected; they enable the bridging of design with two important notions within the scope of the present research: complexity and innovation. The material included in this chapter is indicative of the author's approach and understanding of the field, hoping that some of this distilled knowledge can provide a solid platform not only for this dissertation, but also for future research.

Keywords for this chapter: *design theory, C-K theory, axiomatic design, Simon, design complexity*

2.1 Definitions and introductory remarks

It comes as a conclusion from a four-year experience in design research that often, there is a lack of common ground and understanding among the design research community regarding fundamental notions and terms related to the field. Motivated by the fact that 'design' and 'design theory' constitute core notions of this study, a sound definition of them (even a contestable or subjective one) stemmed from a systematic literature review, was considered as a proper way to open this section.

There is a wide range of activities and professions that come under the umbrella of the term '***design***'. Buchanan (1992b) points out that there is no single definition of design which "*adequately covers the diversity of ideas and methods gathered together under the label*". The Oxford dictionary of English language (Soanes et al. 2006) defines design as the "*art or action of conceiving of and producing a plan or drawing of something before it is made*". Also, Simon's (1996) definition of it as a process aiming at "*changing existing situations into preferred ones*" is a popular one among the design research community.

For the purpose of this research and discussion, design will mean ***synthesis*** (Simon 1995). Synthesis of shapes, objects, ideas, processes, policies, technologies and so on, aiming at the achievement of a goal. If the synthesised elements are seen as building blocks, the uniqueness of any design lies in the fact that these building blocks have never been put together in exactly the same way.

It is on purpose that the definition assigned to design in the above paragraph is so wide. This was done so that it can apply to all design practices, regardless the semantic context within which the term is used. This, of course, also leads to a complication, making the task of creating a theory that covers such a wide range of meanings and actions even more challenging.

Dealing with design is difficult, not only due to the wide range of activities it covers, but also because of its own nature. The only way to understand design and what differentiates it from other activities is by engaging in ***design theory***. If someone attempted to give a definition to design theory, this would be a set -or continuum- of theories, each one of which can describe certain aspects of design practice or thinking. Although (Le Masson and Weil 2013) point out that design theories do not actually describe, but instead rationalise design and add new forms to it. This discussion goes beyond the scope of this research. In more simple and practical terms, the term 'theory' could refer to any piece of knowledge that is transferrable. Even if a theory is not properly consolidated or framed yet, it can sometimes entail observational, experimental, experience-based or intuitional elements.

But how are new theories developed? The need for creation of a new theory results from a lack of an existing one that can sufficiently describe specific phenomena. When a new theory is established, apart from any new contribution, it also needs to contain (even in a different context or expression) all the notions and phenomena entailed in the previous ones. Like this, the compatibility and continuation between theories is maintained (see also related work from Hodges et al. on the "f*our criteria for Design theories*" (2017)). Hence, in design, as in any other discipline or field, theories are not refuted, but *extended*.

The end goal of design theorists is to unify all theories of design into one which can sufficiently describe all the design activities and phenomena, exactly in the same way that physicists aim at the creation of a theory which describes every physical phenomenon in

the universe. Regardless if such a scenario is ideal due to limitations and lack of resources (e.g. infinite time and knowledge), this will always remain the purpose of all theories.

2.2 An approach to reviewing design theory literature

2.2.1 Common confusions regarding design theory

This section is the result of extended discussion with fellow scholar design researchers combined with the experience of conducting a PhD in this thematic area. There is a plethora of literature which theorises about design and discusses the various approaches to it. The first and most difficult challenge faced, is to classify which of these articles, books or conference papers constitute a piece of a 'formal design theory'. For example, there are numerous (even contemporary) papers about "design problem solving" (Chrysikou and Weisberg 2005; Goldschmidt and Smolkov 2006; Casakin 2007), whilst in the formal design theory, it has been commonly accepted that design is not a problem-solving activity (Hatchuel et al. 2018). Therefore, the presentation of a proposed methodology for conducting a systematic literature review of design theory was considered as a decent contribution to new researchers in the field. The aim of such a review is the identification of articles which, even if they do not comprise an extensive list, they can build a platform of sufficient, pertinent and up-to-date information to build upon.

Design theory is a very demanding research field. Not only due to the complexity related to design as a practice, but also because of the numerous self-conscious activities involved in the design process such as ideation, evaluation, decision-making, problem-solving, optimisation, modelling, knowledge generation and conceptual expansion. However, none of the named cognitive activities alone can sufficiently describe Design and this is what differentiates it from other disciplines (Le Masson et al. 2013). These theoretical complications are further explained and analysed later on in the thesis, but a key message at this point is that even the execution of a literature review in design theory presents more complications than it would normally do in any other field.

An issue that becomes evident when looking for relevant information is the abundance of (often divergent) literature sources that appear. Indeed, the term 'design theory' is mostly used by fields and disciplines which are irrelevant to the topic of interest. This is due to

the numerous meanings of the terms “design” and “theory”, a fact that leads to their usage in many different semantic contexts.

In order to prove the above statement, a literature research was conducted on October the 17th, 2018 using Scopus®, the world’s largest database of peer-reviewed literature. The search looked for publications which contain the exact term “design theory” (including quotes) in their list of keywords. The 2,441 articles were then categorised based on their field or discipline (Figure B-1 of appendix B).

A first conclusion is that Design does not come into sight as a discipline. This causes an important implication, which has to be addressed. In an ideal world, Design would appear as an individual research discipline and accordingly, design theory would be placed under this category. But this is not the case.

One way to address this would be to narrow down the results by looking for papers containing the term “design theory” in their title, rather than in their list of keywords. Naturally, the number of generated results has now decreased to 1,039, as shown in Figure B-2 in appendix B.

Even with this search criterion though, the number of results remains too big to be processed and the thematic fields fairly broad and diverge. A logical step of action would be to eliminate all the seemingly irrelevant disciplines, such as ‘Medicine’, ‘Chemistry’, ‘Dentistry’, ‘Chemical Engineering’ and so on, but even so, there are still a couple of issues to be resolved. The first one is that a researcher who knows nothing about the field cannot be sure whether design theory falls only under one category, for instance ‘Engineering’, which seems to be most relevant. On the contrary, it will soon become evident that some very relevant articles would have been excluded if Computer Science and Decision Sciences were eliminated from the list. The second issue is that even if the results are limited only to ‘Engineering’ papers, the number of papers remains too big to be processed (i.e. 588).

As a result, another methodology is required to get a fairly small number of papers, which, however, contain all the essential information needed.

2.2.2 A proposed methodology for a systematic literature review of design theory

A proposed methodology which leads to the key papers in the field of design theory is the one presented in Figure 4, in the form of a PRISMA (Preferred Reporting Items for Systematic Reviews) flow diagram (Moher et al. 2009). The database used for the purpose of this demonstration is Scopus®, but the same or similar methodology can be followed in any other database as well.

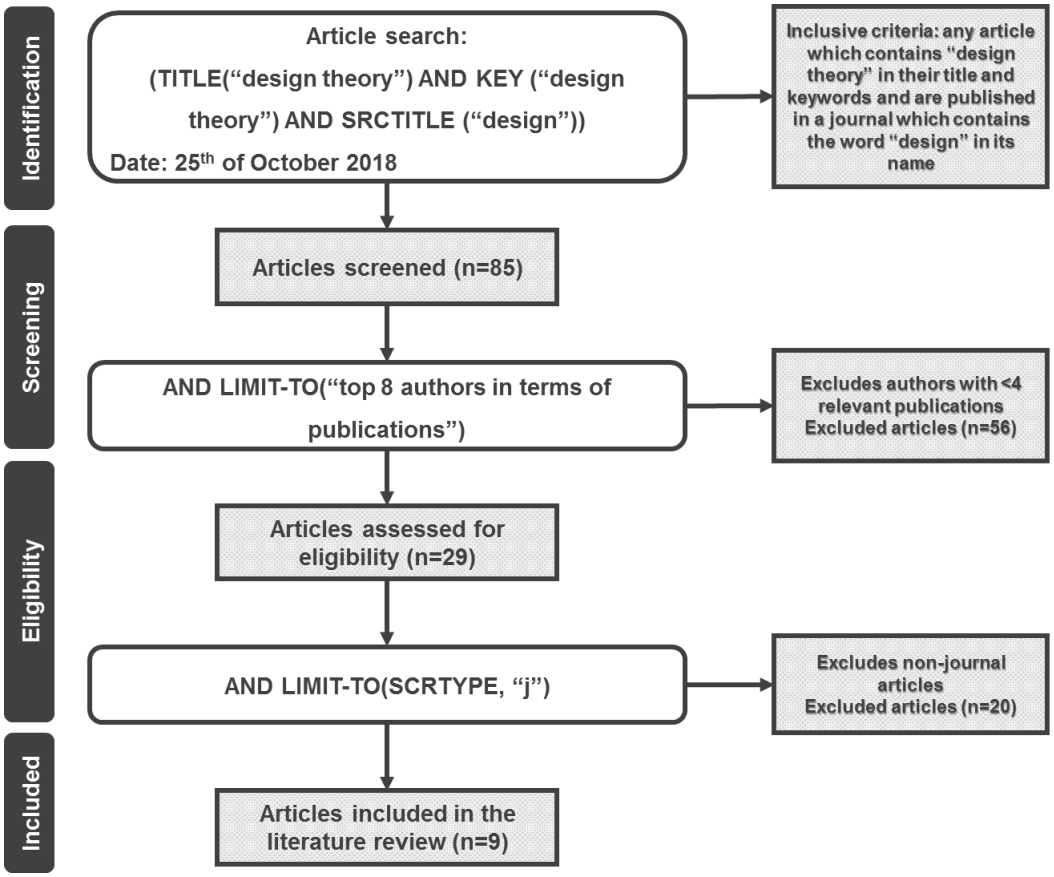


Figure 4. A **PRISMA flow diagram** of a literature review aiming at the identification of key papers in the field of **design theory** (as to 25/10/2018).

The generated results (as shown in Table B-1 of appendix B) are, in fact, some of the most important articles concerning design theory, either being written by influential authors in the field, or reviewing the work of others. For example, the most cited article in the result table, i.e. (Hatchuel and Weil 2009), presents an advanced formulation of the C-K theory, the most contemporary theory we have in design to date. Hatchuel et al. (2018) discuss how modern design theory will contribute to other disciplines and academic communities and the impact it will have on industrial innovation and R&D projects. The review paper written by (Le Masson et al. 2013) reviews the history and

advancements of the field, including the recent efforts to form a formal design theory, namely Function-Behaviour-Structure (Gero 1990), General Design Theory (Yoshikawa 1981), Axiomatic Design (Suh 1998), Coupled Design Process (Braha and Reich 2003), Infused Design and C-K (Hatchuel and Weil 2009). Table 1 reveals the names of some prolific authors in modern design theory and the journal that tends to publish the majority of articles related to the field. Namely, the journal of research in engineering design (Res Eng Des) seems to be predominant in this space, as it entails 8 out of the 9 publications resulted.

It is only natural that a list of nine articles cannot be extensive. There are some original articles, as well as several interesting articles that link design theory to other disciplines, that are not included. However, the purpose of this systematic literature review is to provide a short list of articles, containing all the essential information needed to get an understanding of design theory's roots and latest advancements. Thus, from this perspective, the proposed methodology fulfils its goal.

2.2.3 Key Findings from the literature review

Design theory constitutes only one of the sub-fields of design research. The latter was emerged as a recognisable academic field in the 1960s, through the 'design method movement' (Cross 1993) and refers to any subject of enquiry concerning the design process. The subject soon became an academic field, known as 'design methodology'.

Konda et al. (1992), present a comprehensive map of design methods and theories as of 1992, identifying more than 35 distinct theoretical approaches and schools of design research at that time. Since almost three decades have passed since then, this list has naturally expanded a lot. Nowadays, the design research taxonomy covers a wide range of theoretical approaches to design, regarding design philosophy/epistemology (study of design knowledge and thinking), design practices and processes, design phenomenology (study of the form and configuration of artefacts) and design conceptualisation (the act of generating new concepts) (see also (Cross 1999) for a disciplined conversation on design research).

The takeaway message is that design theory is not concerned with the methodology or the science (meaning 'study') of design, but mainly with the encapsulation, rationalisation

and depiction of design as a generative activity. This is important to remember when looking in the design research literature for design theory work, and it also explains why important authors that conduct research in the space of other subfields did not appear in the systematic review presented above.

2.3 The beginning of design theory

Simon's goal was to explain complex, uncomprehensive human behaviour with simple - but still informed and constrained- decision rules. He always maintained that design and creativity are special forms of problem-solving and decision-making. We might now know that they both constitute restricted forms of design, but still, Simon was one of the few authors in social and psychological research to understand the theoretical importance of design. Back at his time, few economists would have the insight and shrewdness to thing that a good theory of design is important for their own discipline. Until then, most economic researchers were attached to the idea that the technical and practical meaning of 'rational behaviour' was optimisation, either in its simple, deterministic form, or in more sophisticated ones. Thus, the shift of economic and organisational research towards a decision paradigm has been a complex process.

Simon's conceptual idea of "bounded rationality" was a refutation of all the classic hypotheses of optimal choice, which assumed perfect knowledge of alternatives and consequences, ideal preferences and so on. He was critical of maximisation theories and he persistently viewed the concept of rationality through the lenses of an empirically-grounded theory of human problem-solving. Simon also proposed to build such theory of decision-making and problem-solving on a 'satisficing' principle, where satisfaction should also be endogenously defined within the decision process. Consequently, he often insisted that facing a problem is followed by simultaneous discussions of alternatives, goals, constraints and procedures (time, computational costs, etc.). In his view, decision-making was a natural phenomenon that could be studied by computer simulation, empirical analysis or laboratory experiments and he attempted to investigate Design within the scope of the same decision-making paradigm (see for example (Newell et al. 1958)).

Simon also related Design with what he called 'ill-structured problems', which can be

defined as situations where many factors interact with each other, information is unclear, and their exact structure remains blurry. He revitalised the distinction between "natural sciences" and "sciences of the artificial". He defined the former as sciences which "study how the world is and exclude the normative" and the latter as the ones which examine "how thigs ought to be in order to attain goals" (Simon 1996). He gave rise to a major change and evolution of the economic and social sciences, not only by criticising the theory of 'perfect choice', but also by understanding the necessity to build Design as a theory.

Although Simon's work triggered a discussion around how a theory of design should look like, it was incomplete simply because problem-solving and design theory present significant differences. Problem-solving presumes all the classics of bounded rationality, namely the impact of computational cost on solution exploration, a strong knowledge of strategies and the generation of small number of evaluable and comparable solutions. Consequently, it leads to a countable set of solutions. Design, on the other hand, often leads to unexpected expansions of initial concepts, undefined 'problems' and 'constraints', unexpected areas of learning process, social interaction and involvement of multiple stakeholders who assess proposed solutions based on their own criteria. Therefore, design theory leads to a non-countable set of potential outcomes, violating the classic concept of standard set theory.

To conclude with, during the 90s and 2000s, and based on the above, it became evident that a new design theory should be developed in order to address these issues. A theory that does not rely any more on problem-solving and decision-making, but which is able to sufficiently describe this unexpected, non-countable set of potential outcomes.

2.4 A review of C-K theory and C-K/Ma model

2.4.1 Introduction to C-K theory and the notion of generativity

For a long time, design theories were attempting to explain design using either decision or creativity theory. Decision theory (or rigorous formal reasoning) goes down to decision-making, problem-solving and combinatorics. However, all these schools of design theory fail to capture significant features of design and especially the idea of the 'unknown' (namely the unknown aspects and concepts explored or created by designers).

Formal reasoning relies on a rationale of optimisation, the assumption of an integrated knowledge structure and a closed-world hypothesis (Hatchuel and Weil 2007; Hatchuel et al. 2018). Creativity, on the other hand, describes nothing but a set of psychological phenomena which focus on ideation within existing bodies of knowledge. The element missing is the ability to create one or several entities based upon -but going beyond- the creative idea (Le Masson et al. 2011).

Modern design theory shows that design is neither formal reasoning, nor creativity. It is about a skill called ***generativity***. Generativity is defined as the capability to generate new propositions that are made of known building blocks but are still different from all previously known combinations of these building blocks (Hatchuel et al. 2013). This definition of generativity is in alignment with the definition given to design. In other words, it echoes why design is in fact an expression of generativity.

The notion of generativity is included in a design theory called ***C-K theory*** (Hatchuel and Weil 2003, 2009). The C-K theory contains and expands the already established theories of design: GDT (Yoshikawa 1981; Tomiyama 1994), AD (Suh 1998, 1999), CDP (Braha and Reich 2003) and ID (Shai et al. 2013). The underlying principle behind C-K theory is the interaction between two spaces which differ in terms of structure and logic: the knowledge space (K-space) and the space of concepts (C-space). The K-space contains 'decidable propositions' in the form of logical variables which can get 'True' or 'False' as values. On the other hand, the C-space contains 'undecidable propositions', meaning that they cannot be immediately accepted or rejected as there is not the corresponding information in the K-space to do so. The way they interact with each other comprises the fundamental propositions of the theory.

The movement between the two spaces can be described by four primary operators: C→C, C→K (conjunction operator), K→C (disjunction operator) and K→K. The K to K operators correspond to the already known operations of formal reasoning, e.g. inference, deduction, decision and optimisation (Le Masson et al. 2017). The K to C operator refers to the creation of an undecidable proposition based on a decidable proposition in K. Conversely, the C to K operator describes the creation of a decidable proposition based upon an undecidable proposition in C. Now it becomes clearer how C-K theory uses the existing decision theories to describe the operations in the K-space and the creativity

theories to demonstrate how the movements from one concept to another occur. But it also shows that design does not necessarily get built on and around existing logical structures, as it is possible to revisit the definitions of objects and the established knowledge that exist in the K-space.

A simplistic explanation of the C-K theory would be the following. Every design process starts with a brief which leads to the first concept created in the C-space, symbolised as C_0. The C-space is constantly informed by the content in the K-space. Various sub-concepts are then explored and developed until a final concept which is not contained in the K-space is generated (hence the term 'generativity'). If the concept is proven to work (i.e. meet the design criteria described in the brief), then it moves to the K-space and can be considered from that point onwards as a known concept. Figure 5 represents this process of generating new concepts and ultimately new knowledge.

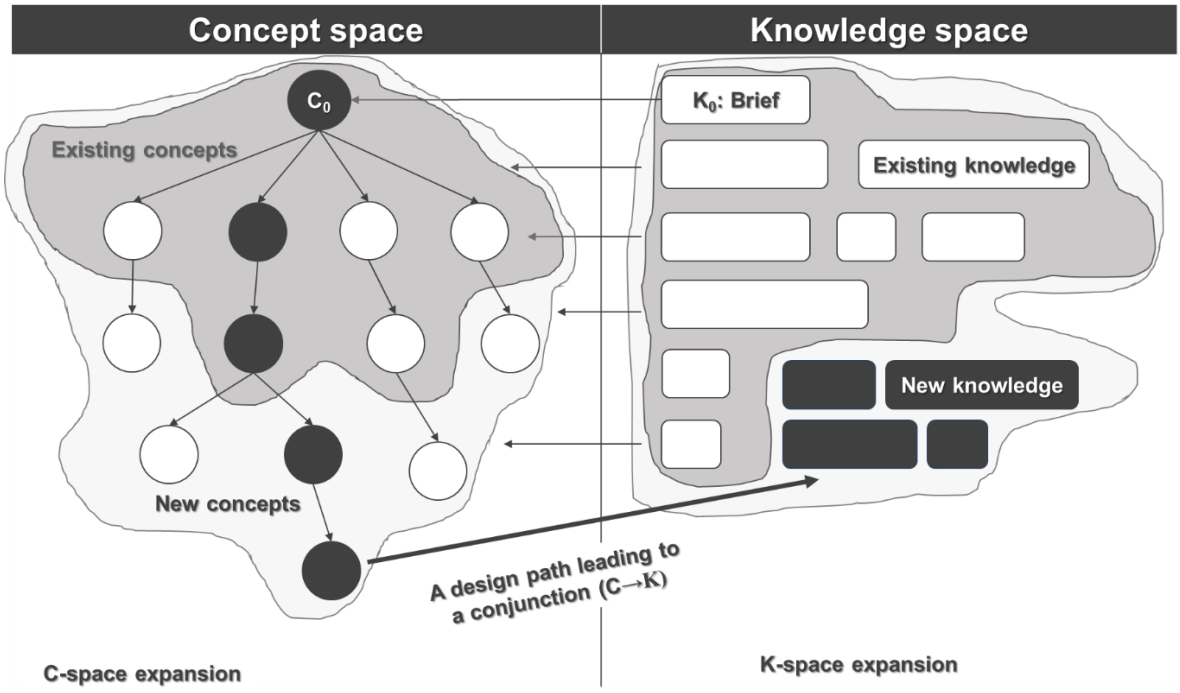


Figure 5. A visual representation of the C-K theory. In order for a conjunction to occur, an expansion both in the C- and K- spaces is required

The main motivation behind the creation of the C-K theory and the introduction of the term 'generativity' is now becoming more evident. The notion of ***innovation*** is not any more a vaguely defined process or activity, but it can be explained based upon a strict and well-defined theory within design. More precisely, innovation can be abstractly described

as the result of generativity.

To summarise, the C-K theory is capable of explaining how techniques (or 'concepts') are born and how they evolve in the design process. In contrary to all the pre-existing design theories which rely solely on formal reasoning or the psychological phenomenon of creativity, C-K provides us with an integrated explanation of the design innovation process. It can also include the element of the 'unknown' in terms of a not yet designed concept or not yet existing knowledge, without theoretical implications.

2.4.2 Measuring generativity - the C-K/Ma model

The previous paragraphs explain how C-K theory complements past theories by introducing generativity as the design phenomenon to address the unexpected expansions of the conceptual space. But can generativity be measured? With the theory as it stands, there seems to be a way of measuring it by defining the level of expansion in the concept and knowledge space. However, such an attempt not only would require a lot of time and effort, but it would also be subjective. What needs to be reminded at this point is that both the K- and C- spaces refer to the individual designer. Thus, it would be extremely dangerous to deduct any conclusions considering their initial dimensions unless the persons conducting the analysis are the designers themselves. An objective model is therefore needed to measure generativity and to also define the impact that a generated concept (invention) has on existing concepts.

To link this effort to similar past attempts, it shall be noted that it is not the first time that the creation of new technical concepts is explored. The basic principles of this process were known since Simondon analysed the logic of "individuation" (1989) to explain how a new 'individual' technology emerges from a 'population' of technologies. There is also an understanding of how a technology stops evolving (see for example Gille's (1987) work on "blocked technical systems"). What the new model needs to bring in, is a way of quantifying the interaction of the newly-developed concept with the wider family of existing concepts. In other words, the measurement of generativity has to rely on the interdependencies between the various technologies.

The creators of C-K theory have proposed a model to measure the impact of a new "technique" on others based on the interdependencies between them (see Le Masson et

al. 2017). The model is called ***C-K/Ma***, with "Ma" being an abbreviation for "Matroid". Matroids in combinatorics (a branch of mathematics) are structures abstracting and generalising linear interdependencies in vector spaces (Whitney 1935). Before a detailed description of the model is given, let us intuitively draw upon the basic ways of generating a concept or technology. When designing a new technology (or technical system) there are basically three possibilities. To:

1. Design a product (defined as the end result of the design process) by relying solely on already existing techniques.

2. Develop a new technique which aims at the development of a new product. This technique needs to be as least pervasive as possible and corresponds to the tasks of a typical engineering department.

3. Design a new technique, aiming at re-ordering all the interdependencies between the other techniques. This technique is characterised as pervasive, since it not only leads to a new design, but it also constitutes itself a necessary component for pre-existing technologies to remain functional (e.g. the steam engine).

Linking the methods described above to the theory of innovation, someone could claim that the second case corresponds to what is often called incremental innovation, whilst the third one to what is known as radical or disruptive innovation.

In a graphic matroid model, any basic technique is represented by an edge t_i. A subset of such elementary techniques forms a technical system. If this is a working system (or technology), then the subset leading to it is called ***dependent***, otherwise it is called ***independent***. In matroid theory, a dependent set is defined a ***cycle***. So, every working technology contains at least one circuit and if it contains exactly one, the working system is called ***minimal***. A set of technologies however, do not necessarily create a working system, or in other words, their elements are not necessarily dependent. Last but not least, if a subset of techniques belonging to a matroid M (a family of techniques) is incompatible to any technique that does not belong to M, it is called a ***flat***. For example, many of the techniques used in the automotive industry form flats, as they are incompatible with the techniques used in other industries.

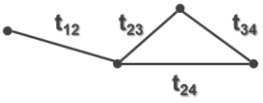
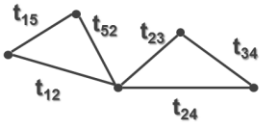
Explanation	Matroid theory	Illustration
Elementary technique t_i	An element in a matroid	
A working system	A dependent set, containing at least one circuit	
A minimal working system	A circuit (or cycle)	
A technology or system of techniques	The matroid M of techniques	
A subset of techniques that is incompatible to any other technique out of the family	A flat extracted from M	

Figure 6. The basic concepts in matroid theory (adaptation from Le Masson et al. 2017)

Now that a way of representing any technical system as a set of techniques has been introduced, the three design approaches mentioned above can be revisited. More precisely, it can be deduced that:

1. Any design relying solely on existing techniques is generated by ***deletion*** or ***contraction***. Deletion refers to skipping an edge, whilst contraction occurs when an edge is removed and its two incident vertices are merged into a new one.

2. The development of a working system by adding a new technique which does not affect the interdependencies between the existing techniques is called ***extension***. Extension can be graphically represented by adding a new edge in between two existing vertices.

3. The addition of a new technique that leads to a new working system in a way that makes the previously independent working systems dependent, corresponds to a ***coextension***. In this case, the interdependencies between the techniques are affected and therefore this expression of generativity is considered as ***pervasive***.

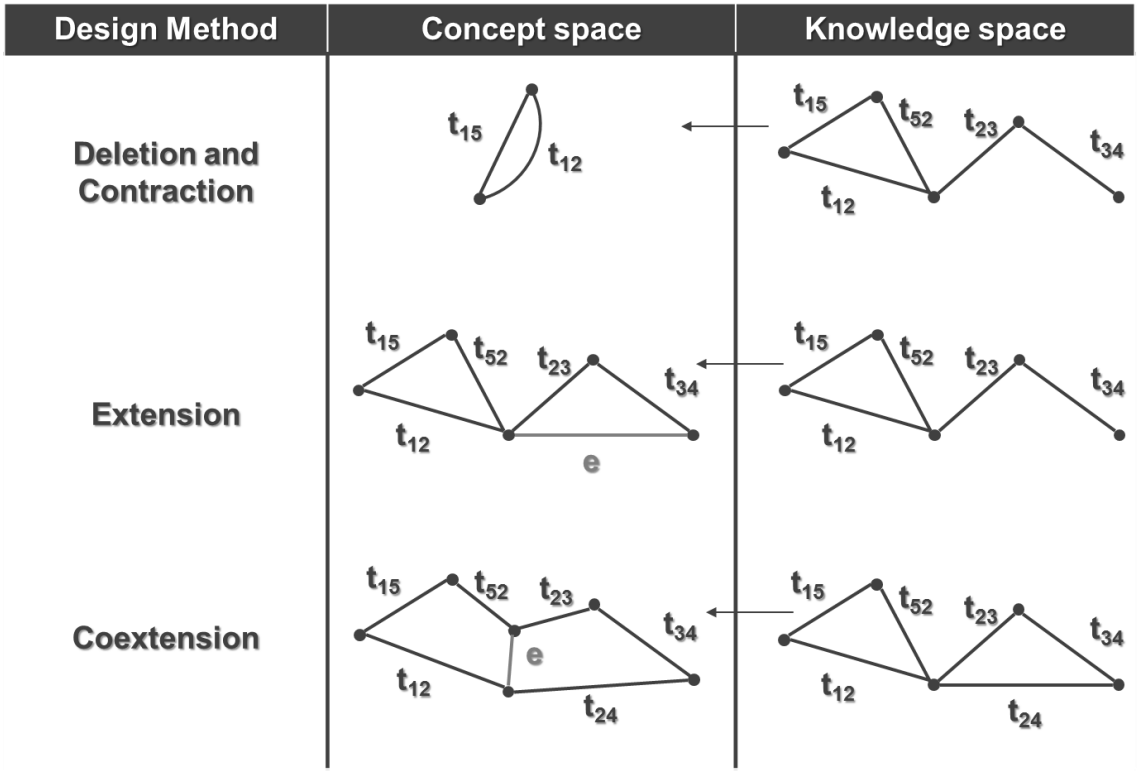


Figure 7. Design by deletion/contraction, extension and coextension (adaptation from Le Masson et al. 2017)

Figure 8 shows an example of each design method if the design in the K-space is a set of common hex key with a handle. In the case of contraction, the handle is removed as the tool can clearly work even without it. In the case of extension, the existing design with the handle is extended so that the handle can include an extra hex key. This extra feature is an edge which does not affect the interdependencies of the previous design, it just enhances it. Finally, the coextension is articulated by the creation of a suitable handle which enables multiple hex keys to coexist in the same tool. This handle design constitutes the edge which changes the interdependencies between the techniques of the existing design. In terms of matroid theory, in the case of coextension, the rank of the matroid increases. This in reality implies that coextension "unlocks" the creation of new designs.

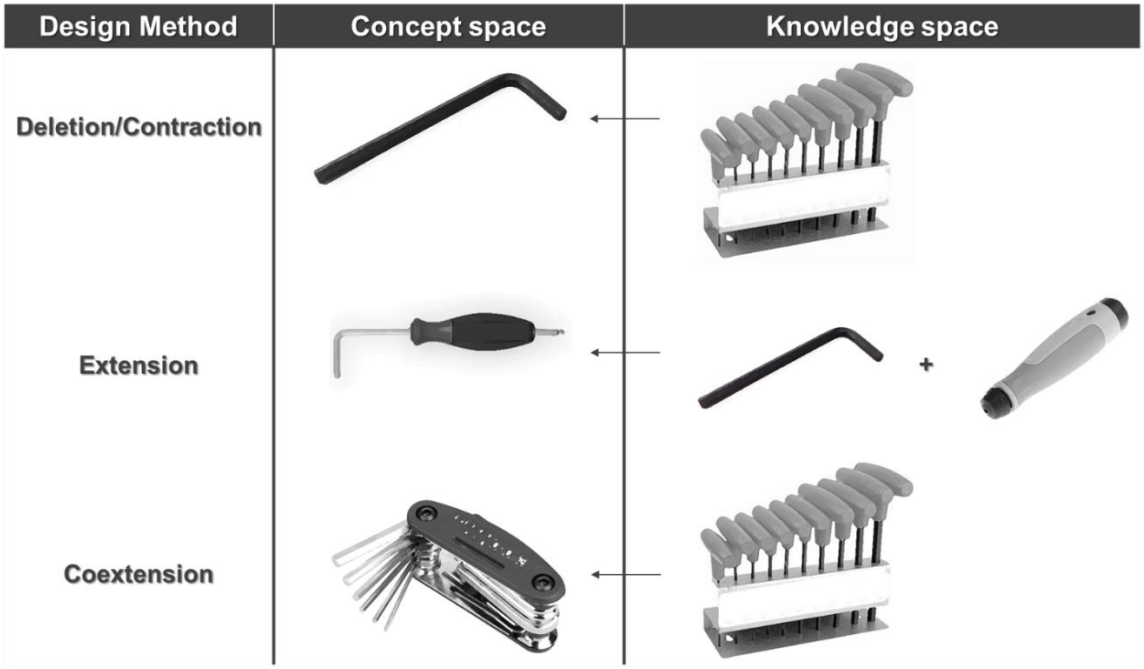


Figure 8. A demonstration of each design technique for the case of a hex key tool

It now becomes clear that generativity can be quantified as the number of newly-added edges. Moreover, a qualitative aspect of generativity can be identified by determining the design method by which the new technologies have been generated (e.g. extension, coextension, or both). Additionally, if we define ***genericity*** as the number of applications that derive from one design (Kokshagina et al. 2013), we can measure the systemic impact of one particular newly-developed technique based on its genericity.

But what is the link between the C-K/Ma model and technological novelty? Although there is still an open debate, a recent quantitative study on US patents (Strumsky and Lobo 2015) showed that there is a significant dominance of combined methods of both ***exploitative*** [extension-based] and ***explorative*** [coextension-based] designs. In more detail, for x number of coextensions, x^n extensions are enabled, where $1 \leq n \leq 2$. In other words, patents correspond to an extension-driven regime, but the patent occurs only when a coextension appears. Or, as previously discussed, the coextension creates genericity by enabling multiple extensions to be developed around it. Therefore, in a novel technology we can expect at least one coextension and several extensions which usually vary from x to x^2, where x is the number of coextensions (Le Masson et al. 2017).

2.4.3 Key learnings from the C-K theory

The C-K theory attempts to explain the *design* process through the notion of *generativity*, which is defined as the generation of new propositions that are made of known building blocks, combined in a unique way. The theory describes design as a constant interaction between the knowledge space (K-space) and the space of concepts (C-space). The end result of generativity is what we would call an 'innovative concept'.

The C-K/Ma model enables the quantification of generativity based on the number of edges developed and the identification of whether the design of a new technique results from contraction, extension or coextension. By linking C-K theory to recent quantitative studies on patents, it can be concluded that novel technologies comprise of at least one coextension and several extensions or deletions around it.

2.5 Design and complexity

2.5.1 Research implications

When the theoretical side of the present research project began, the intention was to approach Design and Science from the perspective of complex problem solving. This attempt would not be completely new, but would rely on Simon's (1996) efforts to explain every human behaviour in terms of rational, informed and constrained decision rules. Simon approached design and creativity in the same way, believing that they constitute special forms of problem-solving activity. His efforts and astuteness to appreciate the importance of design theory to a range of academic fields, such as psychology, computer science and economics were rewarded: he was awarded, among others, with a Turing Award in 1975, a Nobel Prize in Economics in 1978, and a National Medal of Science in 1986.

Despite the importance and influence of Simon's work, recent advancements in design theory showed that Design cannot be considered as a problem-solving or decision-making activity, although they can both be viewed as constrained forms of the design process (Hatchuel 2001). Therefore, the initial research scope was reviewed and another approach, compatible to contemporary theory started being explored. Although problem solving was temporarily put aside, it soon became clear that the matter of complexity did not necessarily have to be left out of the discussion. In fact, there is literature which discusses the relation between design and complexity either within (Jonassen 2000) or

outside (Suh 2007; Elmaraghy et al. 2012) the scope of problem-solving.

The interest in complexity resulted from the practical aspect of this research. For a number of reasons, the examined case study was considered to be a good example of a complex challenge faced by a designer.

For all the reasons and complications mentioned above, in this chapter, as well as in the entire thesis, only perspectives and meanings of complexity which are aligned or somehow compatible with the core principles of design theory are going to be used.

2.5.2 Gap and opportunities

Technological progress and more precisely the rapid advancement in computing, communication, control, information and sensor technologies, has resulted in new dynamic systems, which are characterised by high levels of complexity. The problems that scientists and engineers have earlier faced, could be adequately modelled based on the theories of classical and non-classical mechanics, gravitational laws, chemistry and so on. This is because these problems deal with continuous, time-based quantities and variables such as velocity, acceleration, displacement, gas or fluid flow rate, and pressure. By the term 'continuous', we refer to quantities which take real values as time continuously evolves and can thus be described by ordinary and partial differential equations. However, contemporary problems deal with human-made, dynamic systems which can hardly be described by continuous and time-based variables (Wolpert and Macready 1997). A fact that emerges is that in the past, complexity used to refer more to the size of systems, whilst nowadays, it also arises from the interaction between the underlying rules and structures.

There are three basic complexity limits echoing the fact that was described above, namely that the direct solution of various problems is almost impossible using conventional methods. The first limit, known as the "central limit theorem", indicates that we cannot learn faster than $1/\sqrt{T}$ from a data set, where T is the time spent to collect or simulate the data. The second one, known as the "NP-hard" limit, indicates that there is a class of problems that, due to their nature and given the current computational capabilities, we cannot solve in polynomial time, i.e. in intuitively short time. Finally, the colloquially called "*No-Free-Lunch Theorem*" quantifies the trade-off between the generality and the

efficiency of an algorithm (Wolpert and Macready 1997). That means that if there is a method or technique to solve a problem efficiently given specific constraints and resources, then this method is very limited in terms of the amount of problems it can solve. The three complexity limits are a reminder that there are problems that engineering and science still struggle to solve and a new perspective is therefore needed. Managing to overcome the constraints set by these limits will enable us to solve complex problems in various fields, such as optimisation, traffic control, automation, manufacturing systems and big data (Cassandras and Lafortune 2008).

2.5.3 Axiomatic design: a 'design' theory of complexity

With his work and more precisely the theory of Axiomatic Design (AD), Suh (1998) was one of the first scholars who tried to link Design to the notion of complexity. The first and most obvious challenge he faced is that there was not (and there is still not) a common definition of complexity accepted by scientists, engineers and mathematicians. Even nowadays, the term might refer to various situations, such as the complexity of processes ('computational complexity'), the bits of information needed to describe an object, the effort or time required to manufacture a product, or the length of a task's most compact solution ('algorithmic complexity'). In Suh's AD, complexity is defined as "a measure of uncertainty in achieving the specified functional requirements" (Suh 1999). In other words, complexity in AD is nothing but a probabilistic estimation of whether a functional design requirement is going to be achieved or not.

According to AD, the design world consists of four domains: the customer, the functional, the physical and the process domain. Each domain corresponds to a different set of requirements that need to be met. The customer domain comprises of the attributes set by the customer (***CAs***). The functional domain refers to the functional requirements (***FRs***) of a product, which can be satisfied through specific design parameters (***DPs***) belonging to the physical domain. Finally, to generate a product, as it is specified by the DPs, a process that is characterised by certain variables (***PVs***) needs to be developed. Once the customer requirements are defined, they must be translated into FRs without any external influences, which means without thinking of alternatives that have already been designed in the past. After being identified, the FRs are mapped into the physical domain to generate a design with specific DPs that can satisfy them. Usually, in this process each

FR is mapped to multiple DPs, rather than to just one. A careful selection and consideration of DPs is a prerequisite in order to avoid a negative impact on FRs.

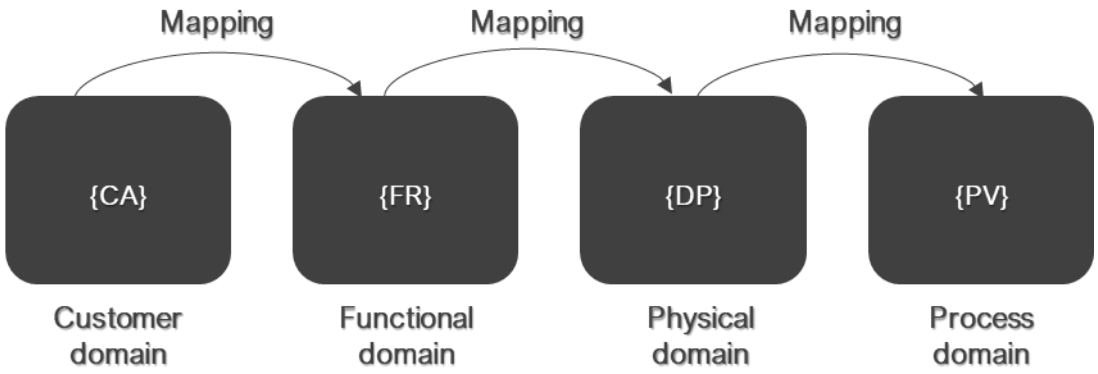


Figure 9. The four domains of the design world, according to **AD** (adaptation from Suh 2007)

AD relies on two basic axioms: the independence and the information axiom. The former suggests that during the mapping process, the FRs need to maintain their independence, meaning that they have to be independent from each other. The latter highlights the need to minimise the information content of the design. For example, if multiple designs satisfy the independence axiom, then the wiser (in terms of simplicity, reliability, robustness and functionality) would be to select the one with the smallest information content.

Axiom 1 (Independence Axiom): FRs need to be independent

Axiom 2 (Information Axiom): Keep the information content of a design to its minimum

The mapping process between the functional and the design domains can be described mathematically as follows:

$$\{FR\} = [A]\{DP\} \qquad \textbf{(Eq. 1)}$$

where [A] is called the *Design Matrix* that maps FR vectors to DPs and is of the following form:

$$[A] = \begin{pmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{pmatrix} \qquad \textbf{(Eq. 2)}$$

In case that the design is linear, As are constants, whilst for a nonlinear design, As are functions of the DPs. There are also two special cases for [A]:

(1) the ***diagonal matrix***, where all A_{ij}=0, apart from those where i=j:

$$[A]=\begin{pmatrix} A_{11} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & A_{nn} \end{pmatrix} \qquad \textbf{(Eq. 3)}$$

(2) the ***triangular matrix***:

$$[A]=\begin{pmatrix} A_{11} & 0 & 0 \\ \vdots & \ddots & 0 \\ A_{31} & \cdots & A_{nn} \end{pmatrix} \qquad \textbf{(Eq. 4)}$$

If the design matrix has either the diagonal or triangular form, then the design satisfies the independence axiom. More precisely, if [A] is diagonal, then the design is called ***uncoupled***, as each of the FRs can be satisfied, irrespectively of DPs. If [A] is triangular, then the independence axiom is satisfied if and only if DPs are determined in an appropriate sequence. In this case, the design is called ***decoupled***. In any other case, where [A] has the form of a full matrix, the design is called ***coupled***.

The reason why the above classification is made, is because it has been shown (Helander and Lin 2002) that from ergonomics point of view, uncoupled designs are the best and that decoupled designs' ergonomic performance improves if they are converted into uncoupled ones. On the other hand, coupled designs should be avoided, as they are not robust enough and cannot survive potential variations that take place in the physical domain or the operating environment (Suh 2007).

But how is information related to all this? Complexity in AD depends on the information available (***I***), where the latter is defined as a logarithmic function of the probability of satisfying specific FRs.

In more detail, the probability P_i of satisfying a given FR*i* is given by:

$$P_i(dr^1 \le FR_i \le dr^u) = \int_{dr^1}^{dr^u} p_s(FR_i)d(FR_i) \qquad \textbf{(Eq. 5)}$$

where dr^1 and dr^u represent the lower and upper limits of the design range respectively.

Information content *I* is defined as a logarithmic function of the probability P_i:

$$I_i = -\log_2 P_i = -\log_2 \int_{dr^1}^{dr^u} p_s(FR_i)d(FR_i) \quad \textbf{(Eq. 6)}$$

Similarly, the information content for satisfying a set of FRs corresponding to an entire system, is the sum of the information content I_i corresponding to a specific FR_i:

$$I = \sum_{i=1}^{n} I_i = \sum_{i=1}^{n} -\log_2 P_i \qquad \textbf{(Eq. 7)}$$

where P_i refers to the probability of satisfying functional requirement FR_i.

Therefore, the complexity of a system is not related to the number of FRs, but it rather depends on the probability I: the lower the information content I is, the less complex a system is, compared to another system with the same number of FRs (Suh 1999).

In AD, there are two kinds of complexity: ***time-independent*** and ***time-dependent complexity***. The former can be further divided into real and imaginary complexity, and the latter into combinatorial and periodic complexity.

Real complexity is defined as "*the measure of uncertainty when the probability of achieving FRs is less than 1.0*", in other words it exists when we know that the design does not meet the FRs at all times (Suh 1999). The overall real complexity is also named as 'absolute complexity' and is equal to the sum of real and imaginary complexity.

Imaginary complexity, on the other hand can be defined as the complexity that is due to the "*uncertainty that arises because of the designer's lack of knowledge or understanding of a specific design*"(Suh 1999).

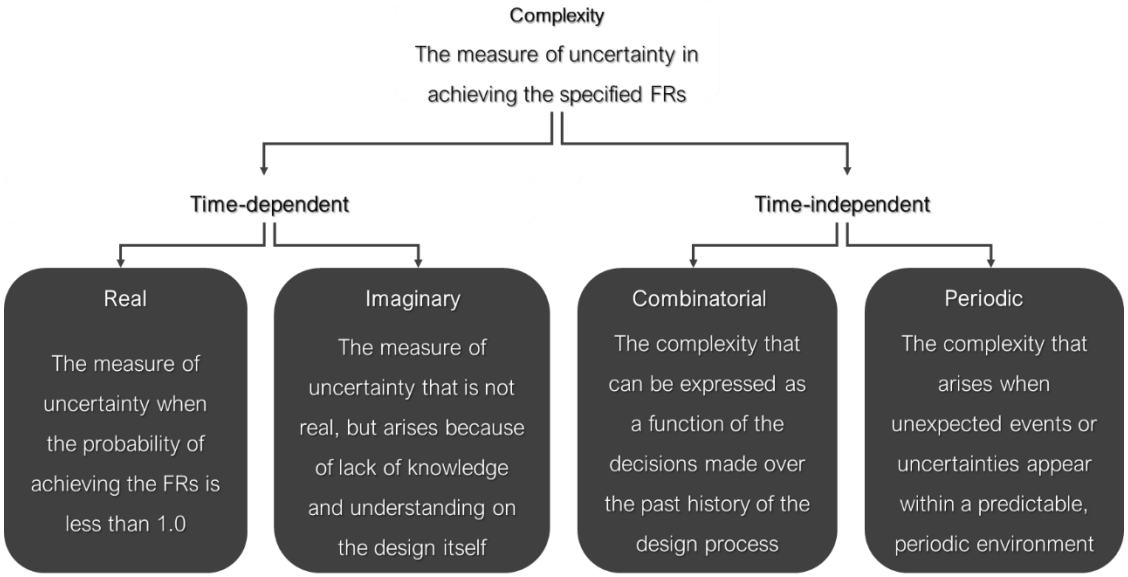


Figure 10. The different **types of complexity**, according to AD

The above classifications of the mapping processes and complexity types facilitates the identification of the exact type of complexity that characterises a design. If these elements are identified, then the level of complexity can be reduced by applying the Independence and Information Axioms.

2.5.4 Key Learnings from AD theory

What is important at this stage is that the notion of complexity as defined in AD's context is particularly useful for this research, as it addresses a fact that other theories of complexity cannot: subjectivity. For example, the component of "imaginary complexity" refers to the situation where the designer does not have the knowledge or experience to address a problem which otherwise is not necessarily complex. As a result, any complications that concern the uncertainty of whether a design project or task is indeed complex or not are avoided. In the frame of this research, like in the C-K and AD theories, the perception of complexity, as well as any other knowledge or experienced-based variable, differs from one person to another. However, this does not mean that the same theoretical approach cannot be applied to a wider community or even the entire humanity. Hence, we can separate and treat differently the complexity that arises from the limited knowledge or abilities of the designer (*imaginary complexity*) from the one that results from the real-world factors that even an expert designer cannot address (*real complexity*).

The second important conclusion has to do with the fact that thanks to AD, the complexity

of a design can be quantified and potentially addressed by isolating and maintaining the independency of functional features and by keeping the information content to its minimum possible level.

2.6 Summary and formation of research question

In this chapter, a specific and quite wide definition is assigned to design as an act of creating ("generating") something new by synthesising pre-existing elements. Through a review of the history of design theory and its latest advancements, it is explained what design theory deals with, what its purpose is and how it evolved over time. It is also justified why it constitutes a difficult and demanding research field and, therefore, a proposed methodology for systematic literature review is provided to assist future research.

The review is used to highlight the distinction between design theory and problem solving and to demonstrate why a 'design problem solving' approach would not be compatible with design theory. This distinction is depicted in Figure 11.

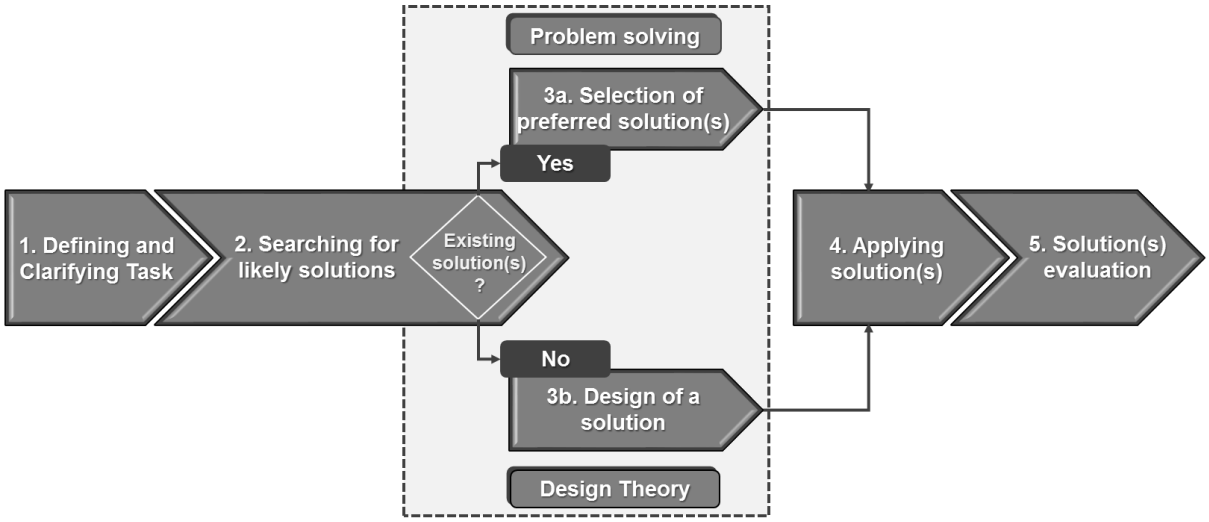


Figure 11. Differentiation between common problem-solving activities and design theory

Some knowledge points critical to the present research are the following:

- Design is defined in the context of this study (as a **proposed definition to the design theory community**) as a '*synthesis of shapes, objects, ideas, processes, policies, technologies and so on, aiming at the achievement of a goal. If the synthesised elements are seen as building blocks, the uniqueness of any design lies in the fact that*

these building blocks have never been put together in exactly the same way' (page 21). This -seemingly generic- definition allows the implementation of the term 'design' in any activity being covered by the above definition, irrelevant to field or discipline. Thus, a **bridging between design and science is enabled**.

- **Design is NOT problem-solving nor decision-making**; it is something wider than these two activities alone, although they both constitute integral parts of the design process.

- **Design is NOT about creativity; it is about generativity**. Creativity is a vaguely-defined psychological term, whilst generativity can be defined as '*the generation of new propositions that are made of known building blocks, combined in a unique way'* (page 30).

There are mainly **three techniques with which any concept is designed**: *deletion*, *extension* and *coextension*. Coextension has been found to be ever-present in US patents, allowing the novel design to become necessary for a range of other designs ('*genericity*').

Regarding technological complexity, new approaches are required to deal with complexity in Engineering and Science. A gap is therefore created for Design to step in. After all, it has been shown in this chapter that any generative activity out of the scope of problem-solving and decision-making belongs by definition to design theory's space, irrelevant to the field or discipline that the generated concept concerns. From this perspective, a first bridging between Design and Science has been achieved. The question remaining to be answered is how exactly is this done? Therefore, the research question that will be attempted to be addressed in the context of the present study, can be phrased as follows:

How are innovative concepts generated in Design and Science?

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3 DESIGN AND DEVELOPMENT OF A NOVEL DRYING SYSTEM

Objective 2: use a case study to gather practical insights on the design of an innovative technology.

This chapter presents the design process of a dewatering, drying and pelletising system that has been developed by from January 2016 and until January 2019 in the context of the 'reinvent the toilet' project funded by the Bill & Melinda Gates Foundation. The presented research activity is used as a case study to gather practical insights from a real-world design project.

Contemporary western-style toilets require a large quantity of clean water and connection to a sewerage system to operate, but 2.3 billion people remain without access to improved sanitation. For this part of the globe's population, a waterless and zero-energy toilet would constitute a solution of high potential. A critical technology for this toilet is a system of dewatering, drying and pelletising human faeces in order to convert it into combustible matter. Incineration is used to reduce biomass and to remove pathogens.

Keywords for this chapter: *drying technology, dryer, conceptual design, design-led innovation*

3.1 Problem statement

Since July 2010, through Resolution 64/292, access to water and sanitation are legally acknowledged as essential elements of adequate living standards by the United Nations Human Rights Council (The United Nations 2010). However, approximately 2.3 billion people around the globe still remain without access to improved sanitation, using drinking sources contaminated with faeces and 892 million people currently resort to open defecation (WHO 2017). The sad reality is that poor sanitation is estimated to cause over 300,000 child deaths per year and the problem is set to worsen as urban population in developing countries is projected to surpass the number of 5 billion people by 2050 (United Nations Department of Economic and Social Affairs 2014).

Motivated by this problem, a group of researchers at Cranfield University are developing

a self-sustained, waterless and household-scaled toilet aspiring to treat human waste on site. The 'Nanomembrane toilet' is part of the 'reinvent the toilet' challenge, set by the Water, Sanitation & Hygiene programme of the Bill & Melinda Gates Foundation, aims to treat human waste on site and to recycle any useful resources without generating hazardous products (Parker 2014; Hanak et al. 2016). An essential part of the toilet is a drying and pelletising device which receives the human waste and converts it into combustible matter. The R&D activities for the drying system were approved by Cranfield University's Research Ethics Working Committee (CURES/2068/2016 and CURES/2393/2017 – see Appendix C).

The Nano Membrane toilet will be able to treat human waste on-site without external energy or water. It is designed for single-household use (equivalent to 10 people) and will accept urine and faeces as a mixture. The flush uses a rotating mechanism without using any water. After the solids (faeces) settle inside the tank, loosely bound water (mostly from urine) is separated using low glass transition temperature hollow-fibre membranes. The nanostructured membranes enable water to transport in the vapour state rather than as a liquid state which yields high rejection of pathogens and some odorous volatile compounds. The water is then collected for reuse at the household level in washing or irrigation applications.

Following release of unbound water, the residual solids are transported by mechanical screw into the dryer, with which the present study is concerned. The solids then enter into a combustor, which converts them into ash and energy. The energy powers the membrane processes, and there may be extra energy for charging mobile phones or other low voltage items.

The Nanomembrane toilet consists of 7 main technologies: a rotating bowl, a swipe mechanism, a settling tank, an Archimedes screw, a dryer, a combustor and a Nanomembrane system. Figure 12 demonstrates where each individual part is located in the system. The parts numbered 1 to 4 constitute the 'front-end' of the toilet and the ones numbered 5 to 7, the 'back-end'.

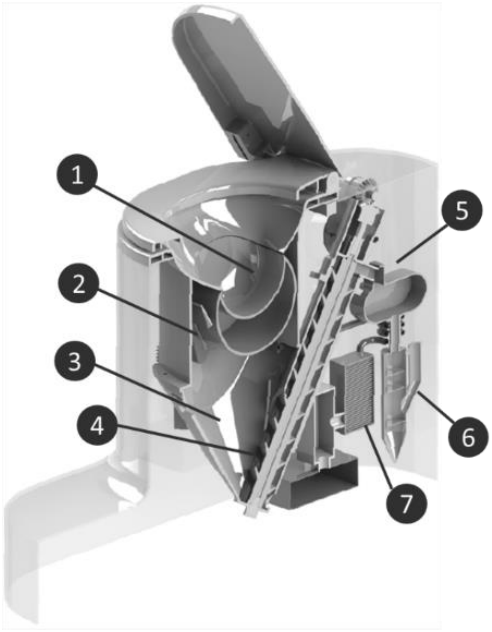

Figure 12. Cranfield University's Nanomembrane toilet. 1-bowl, 2-swipe, 3-tank, 4-screw, 5-dryer, 6-combustor, 7-Nanomembranes

A swipe mechanism, located at the frond-end of the system, cleans the bowl that receives the urine and faeces and empties the waste in a settling tank. The drying device (hereon referred to as '***dryer***') is fed by a screw which lifts the waste from the tank. The dryer aims to prepare the material for combustion, meaning that it needs to decrease the moisture content from around 80 % (Zuma et al. 2015) down to approximately 20 % wet basis moisture content and to form small dried pellets of around 1 gram each. The calculations for the exact moisture level of the dryer input were based on Zuma et al.'s work (2015) who identified that 90% of the samples coming from VIP latrines in Durban, South Africa had a moisture content of between 0.67 and 0.87 g water/g wet mass, with the median moisture level of the faecal sludge being 0.81 g water/g wet mass. These findings were close to Rose and colleagues' ones (Rose et al. 2015), who found that faeces' water composition is 74.6%.

From the above context, it is clear that if the dryer fails to dewater and dry the faeces up to a 20% mc, then the whole system will stop working, as the combustor will be unable to treat the sludge and hence to provide energy to the rest of the components inside the toilet. Therefore, the dryer constitutes a crucial part of the chain.

This chapter presents the design and development of the dryer up to a technology

readiness level (TRL) 3 (Mankins 1995), which corresponds to a 'proof-of-concept' level or, in other words, to a phase where the concept can be considered as validated in terms of the main functional requirements.

3.2 Background

3.2.1 Existing methods and challenges

Drying can be defined as the highly energy-intensive process of liquid-solid separation achieved by heat supply (van't Land 2011) and is accountable for 10-20% of total industrial energy consumption in developed countries (Kemp 2014). As an indication of its intensiveness in terms of energy, in order to heat 1L of water from 15°C to 100°C around 365,150 J of energy are required. This amount of energy is equivalent to the potential energy contained by a car weighting 1.5 tons which hangs 24 m above the ground. Additionally, the evaporation of 1L of water at 100°C under atmospheric pressure requires 2,285,000 J, which corresponds to the potential energy of the same car hanging from 152 m.

Removing water without evaporation (thermal power) and solely relying on mechanical means, is referred to as ***dewatering***. Dewatering alone cannot remove all the moisture for physical reasons. However, due to the energy demands of drying process, it is important to remove mechanically as much liquid as possible (Anlauf 2014). Prior to dewatering, a chemical conditioning procedure usually takes place aiming to generate easily-filtered flocs (Chen et al. 2002). Therefore, the overall process of liquid-solid separation consists of three main stages: conditioning, dewatering and drying (Manara and Zabaniotou 2012). The moisture that can be removed by mechanical means is called ***unbound*** or ***free water*** and the rest of it, which is removed only by applying heat, is referred to as ***bound water***. In turn, bound water can be divided into the following categories: interstitial/capillary moisture, surface moisture and intracellular/chemically bound moisture (Lowe 1995; Chen et al. 2002).

Physical changes that occur during sewage sludge drying can be classified into three stages: wet (70-80% water), pitting (60-65% water), and granular (20-25% water) (Werther and Ogada 1999). The moisture removal of sewage sludge takes place in a temperature range of up to 100-150°C (Shinogi and Kanri 2003).

The main alternatives to mechanical dewatering of sludge are vacuum filters, belt filter presses, centrifuges and membrane filter presses, out of which vacuum filters constitute the oldest method (Chen et al. 2002; Perazzini et al. 2016). According to Kukenberger (1996), the best available dewatering processes (mainly centrifuges) cannot achieve solid contents higher than 25-35% (65-75 % wet basis moisture content).

Drying techniques can be divided into three main categories based on the way the energy (hot air) is supplied to the sludge: convection, conduction and radiation. In convection, the carrier gas (usually air) is used to supply the heat. In the case of conduction, the heat is supplied indirectly through other means and the airflow, which corresponds approximately to 10% of the airflow used in convective process, only serves to remove evaporated moisture. Radiation can be either penetrating (i.e. dielectric drying) or non-penetrating (i.e. infrared, microwave or radio-frequency radiation) and requires a carrier gas to remove evaporated liquid (van't Land 2011). The basic convective dryers are belt, flash, fluidised bed and drum or rotary dryers, among which belt dryers have the widest range of applications. The main groups of conductive dryers are disc, paddle and thin film dryers; these indirect dryers use thermal oil or steam as a heating fluid (Anlauf 2014).

During the last decades, thermochemical processes are viewed as a promising way to produce energy and valuable products from waste residues, as they can be self-sufficient, but important issues related to their energy efficiency, moisture exploitation for hydrogen rich fuel gas production and the expensive antipollution gas equipment counterbalance their key advantage (Khiari et al. 2004; Dennis et al. 2005). Freezing and thawing have been identified as the most efficient way of drying sludge. In particular electrodewatering thawed sludge leads to a significantly higher solid content than non-frozen sludge. However, freezing constitutes a very expensive and energy intensive process and it is only used in cold countries during the winter (Chen et al. 2002). As a result, the challenge of identifying more economical ways for altering the dewaterability of sludge still remains open (Miller et al. 2008).

The plethora of dryers available is due to the fact that different products require different drying times and qualities, and also due to the necessity to transport particulate matter through a dryer (van't Land 2011). The existing dewatering and drying technologies are summarised in Figure 13:

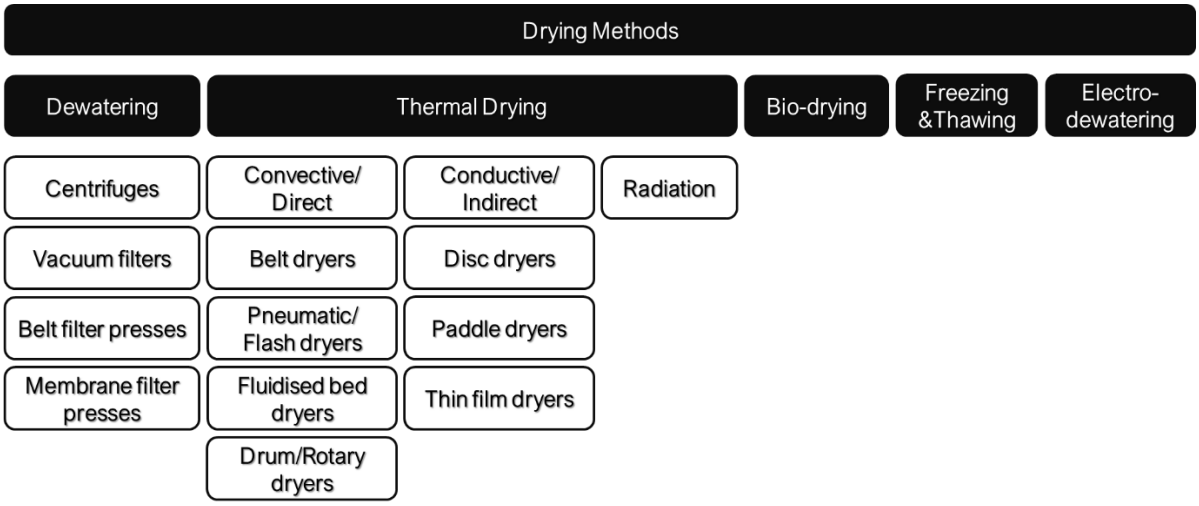

Figure 13. Summary of existing dewatering and drying methods (Anlauf 2014; Perazzini et al. 2016)

Kemp (2014) emphasises that selecting the right type of drying method among almost 40 distinct types of them is a difficult and confusing task. Anlauf (2014) admits that often the dryer choice or design is based on empirical considerations, leading to unsuccessful and inefficient systems. Hence, there is a need for preliminary laboratory experiments to investigate the exact nature of the product which is about to be dried before moving to the selection process.

3.2.2 The value of drying faecal sludge

Human excreta are composites of waste matter discharged from the body (mainly sweat, urine and faeces). The majority of excreta consists of urine and faeces. The organic fraction of faeces consists mainly of bacterial biomass (25-54% of dry solids), undigested carbohydrate, fibre, protein and fat whilst indigested elements comprise its inorganic component. Urine consists of nitrogen, phosphorous and potassium. The nutrients (chemical) concentration and physical composition of both faeces and urine differ according to people's diet and therefore the location (Rose et al. 2015).

Although there is a vast literature on sewage sludge treatment, very limited research has been conducted on the technological aspects of dewatering and drying human excreta, particularly at a household-scale. Therefore, any research to this direction is of significant value to researchers who work on water and sanitation projects, especially for the developing world.

Additionally, given the energy content of human excreta (~25 MJ/kg), which is higher than the one of wood biomass (Onabanjo et al. 2016) and the health benefits resulting from avoiding open defecation, it becomes apparent that there is a high value in developing a technology for home-scaled faecal sludge drying.

Last but not least, the performance and energy balance of the developing waterless toilet rely heavily on the efficiency of the dewatering and drying processes, as they probably constitute the most energy-consuming activities within the system.

Already existing industrial drying processes, as the ones named in Figure 4-3, require a lot of space and a large amount of energy to operate. Thus, the absence of external sources of energy such as electricity, render the task of drying particularly challenging, whilst another constraint is set by the limited space available for the dryer. Moreover, the dried matter resulting from the dryer has to be of high quality in terms of consistency and the drying cycle needs to be completed within a reasonable period of time to maintain the combustor's operation.

Despite these challenges, drying faecal matter deriving from a single, home-scaled toilet does not involve many of the typical difficulties faced by general waste treatment processes, namely the diversity of origins and the heterogeneity of physical, chemical and biological properties (Perazzini et al. 2016).

3.3 Methodology

The project execution can be depicted using the design process model presented in chapter 3 of the dissertation. As a first step, the design objectives were clarified based on collected information (S_0). The functions required were then established and the search for alternative solutions began (S_1). As this chapter concerns the development of the dryer only up to a TRL 3, the aforementioned stages the ones that monopolise its content. More precisely, the establishment of functions and requirements, the determination of characteristics, the generation and evaluation of alternatives, as well as the rapid prototyping activities belong to this phase. Figure 14 illustrates the methodology followed to develop the dryer.

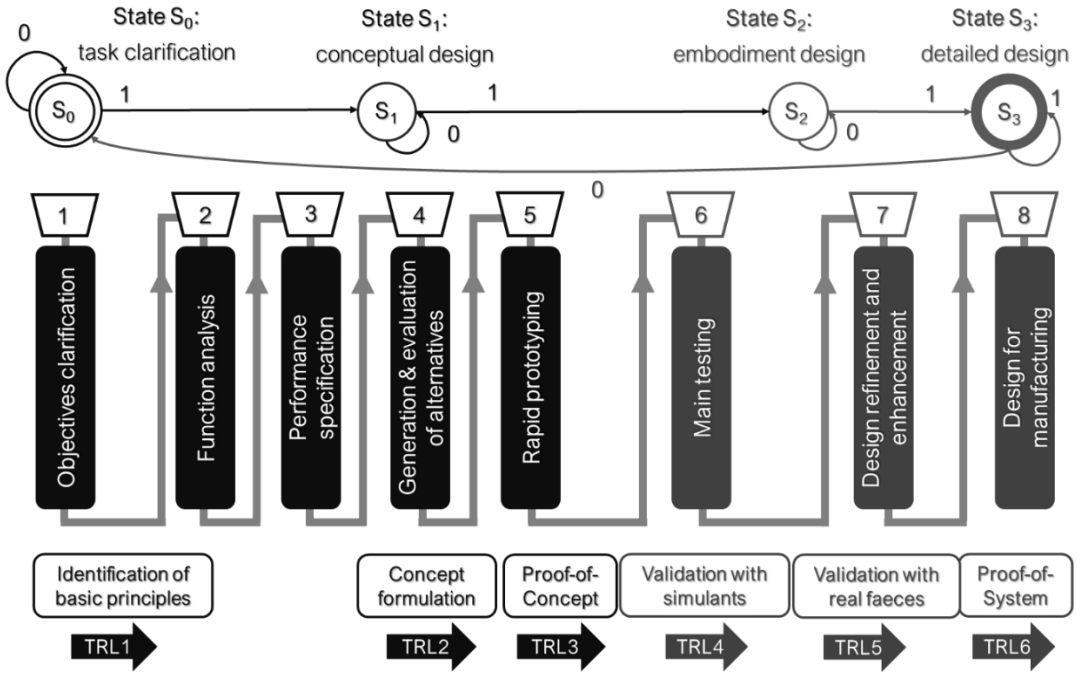

Figure 14. The Dryer design methodology. In dark grey: the stages concerned in this chapter

The phases shown in dark grey colour are the ones that this chapter is concerned with and thus, the ones that will be further analysed below. The methodology depicted in figure 14, could be considered as one of the main contributions to knowledge of this study, as it will be shown that it led to a successful design.

3.4 Dryer design and development

3.4.1 Objectives identification

The original brief that was presented to the dryer design team was defined based upon the expected performance of the screw and the estimated needs of the combustor. From early on in the project, it was clear that a device was needed to dry the sludge that comes out from the screw and to convert it into combustible matter. Hence, this inevitably became the first and most clear objective. A certain period of time would then follow until the remaining objectives related to the design of the dryer were clearly defined. These started being formed after extensive communication with the research and development teams responsible for the remaining components of the system.

The combustion team highlighted the importance of getting pellets of consistent moisture content (i.e. 20 wt. % mc) and calorific value, while the screw team, clarified that the

sludge provided by the screw would not exceed a solid content of 18%. The scope of the project also set strict constraints in terms of energy consumption, as the system should be self-sustained. In addition, since the toilet should be household-scaled, there were limitations in terms of size and shape. Additional requirements, such as technological simplicity, as low manufacturing cost as possible, relatively long lifespan, robustness, safety, survivability and easy connectivity with the rest of the subsystems, were also mentioned during the preliminary scoping meetings.

In order to complement the findings from the meetings with other research teams, a series of simple lab-based experiments were conducted using simulants, aiming to gather some practical insights from sludge drying. The conclusions from these experiments indicated that reducing the thickness of the paste leads to an increase in the efficiency of the drying process. Moreover, a sloped surface would help to remove the unbound moisture, whilst stickiness was identified as one of the key characteristics of the sludge, meaning that a scraping mechanism would probably have to be used. The experiments also showed that convective heat transfer would be more efficient than conductive for a given amount of time but, interestingly enough, it was also found that using a metallic surface would allow the dryer to combine the benefits of both convection and conduction. Last but not least, a temperature of around 200°C was used for these initial experiments, but the combustion team noticed that the dry flocs that were deriving were over-dried and thus lacked the required nutrients for the combustion process to take place. Therefore, a reduction of temperature, along with an increase of the drying time was needed.

A literature review was then undertaken to get a better understanding of the chemical characteristics of waste sludge, the existing processes of sludge treatment and the state-of-the-art drying technologies. The main conclusions that derived from the literature review were the following:

1. All conventional mechanical dewatering systems involve pressure.

2. Time can be more important than pressure in achieving high cake solids contents. More precisely, it has been inferred that applying a high pressure too early in the dewatering process forms an impermeable layer of cake through which the rest of the cake water needs to flow.

3. The filtration rate can increase by increasing pressure.

4. Mechanical dewatering is not enough to dry the faeces up to the desired level. A drying method, therefore a procedure which relies on heat, is needed.

5. A temperature range of 100-150°C is required to remove the moisture; this temperature range, however, does not guarantee that the solid content will be of the desired levels.

As a next step and based upon the above findings, the objectives of the to-be drying technology were classified into essential (necessary) and desirable (would be nice to have) ones. The essential objectives concerning the drying process, such as achieving the desired moisture content in a consistent way and using as much energy generated by the other sub-systems as possible, are shown in Figure 15.

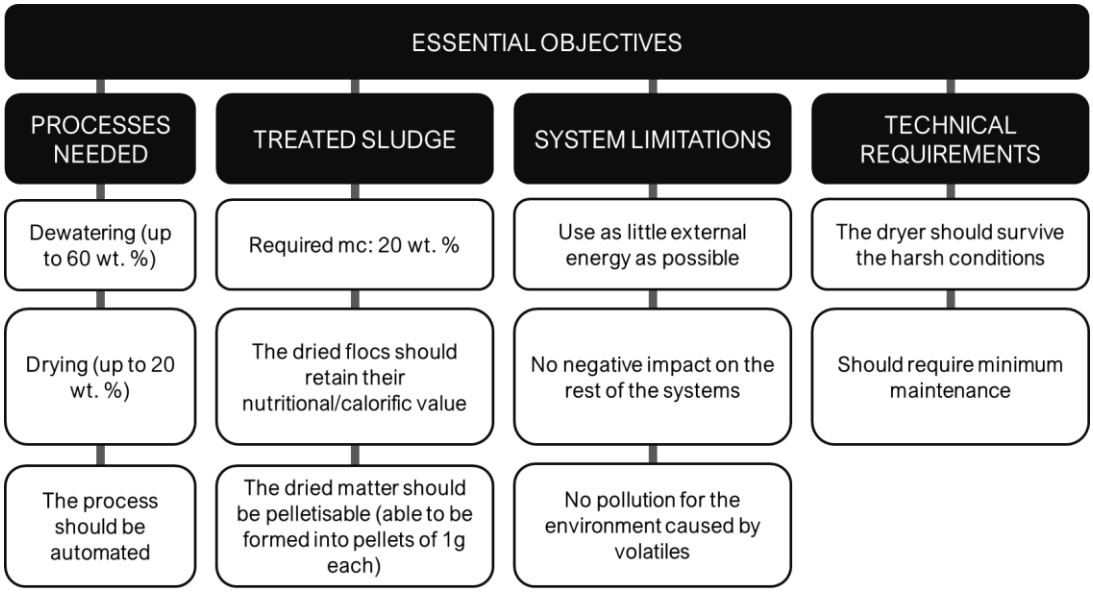

Figure 15. The objectives tree formulated at the end of the first stage of the design process

3.4.2 Establishing functions

In the design process, the objectives tree contains information which refers to different levels of detail or generality. The main realisation from the first stage of objectives clarification was the fact that the challenging task of drying faecal sludge can be broken down to three main functions: mechanical dewatering to bring the moisture content down to about 60% wet basis moisture content, thermal drying to reach 20% wet basis moisture content and finally, pelletisation to form small pellets of 1-1.5g each. At this stage, it was important to focus on these three essential functions even if it was unknown how they

exactly they were going to be achieved. That means that each function was about to be represented as 'black box' with certain inputs and outputs. In order to construct the function diagram for the dryer, the following steps occurred:

1. The overall function was expressed in terms of inputs into outputs (faecal sludge in – dried flocs out).

2. The overall function was broken down into the three essential sub-functions (mechanical dewatering, thermal drying and pellet formation).

3. A block diagram was drawn showing the interactions between the sub-function and their corresponding inputs and outputs.

4. The system boundary was drawn. They system boundary defines the functional limits for the device to be designed.

The function analysis block diagram that derived from the procedure is shown in Figure 16.

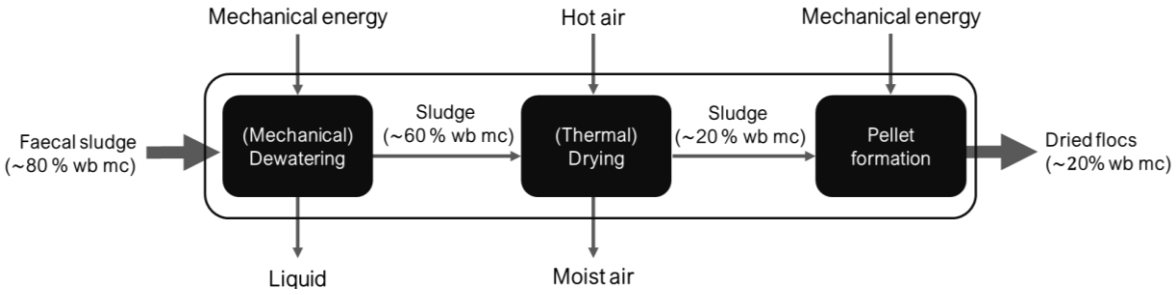

Figure 16. Function analysis block diagram for the dryer (% wb mc stands for % water basis moisture content)

3.4.3 Setting requirements

When the initial objectives were identified and the function analysis for the dryer to be designed became clear, the performance specification document could be drafted. The purpose of this document is to set and depict on a piece of paper the targets that need to be met. Something that needs to be clarified at this point is that not all the objectives and functions are performance specifications. The role of the performance specification document is exactly to bring into consideration the restrictions and boundaries set by the system or the project and convert these objectives and functions into tangible

requirements. Thus, the requirements (essential or desirable) for the dryer were sixteen in total and are included in Table 1. The first three requirements correspond to the main sub-functions needed to achieve the dryer's main goal and the rest are concerned with other system- or project-related considerations.

Table 1. Performance specification document for the dryer

Requirement	Description
FR1	Dewater: reduce the wet basis moisture content of faecal sludge from 80% to 60%
FR2	Dry: reduce the wet basis moisture content of faecal sludge from 60% to 20%
FR3	Pelletisable matter should be produced
FR4	Use no external energy source for the drying process (other than the exhaust gas)
FR5	Use no external source of power for driving the mechanical parts
FR6	Retain calorific value of faeces
FR7	Small space requirements
FR8	Refrain circulation of contaminated air
FR9	Refrain odour leak
FR10	Minimum maintenance
FR11	Robustness to survive 'harsh' environments
FR12	The lifespan of the dryer should be at least as long as the overall's toilet – 3-5 years
FR13	Relatively low cost
FR14	Neutrality in terms of impact
FR15	The whole process should be automated or semi-automated

FR16	The dryer should be able to process input other than faeces (e.g. toilet paper and feminine hygiene products)

The performance specification document was circulated around the various teams working on the project and also as a benchmark for assessing the performance and suitability of the technology to be designed.

3.4.4 Generation and evaluation of alternatives

As soon as the performance specification document was drafted, an idea generation phase began, looking for concepts able to meet the requirements specified above. The drying system should be able to dewater sludge, dry it, scrape off the dried flocs, collect and remove the unbound water. The various alternative technologies identified were assessed in order to select the ones that seemed to lead to viable solutions, taking into consideration the existing constraints and available resources. The morphological chart method was used to illustrate the alternatives (Figure 17).

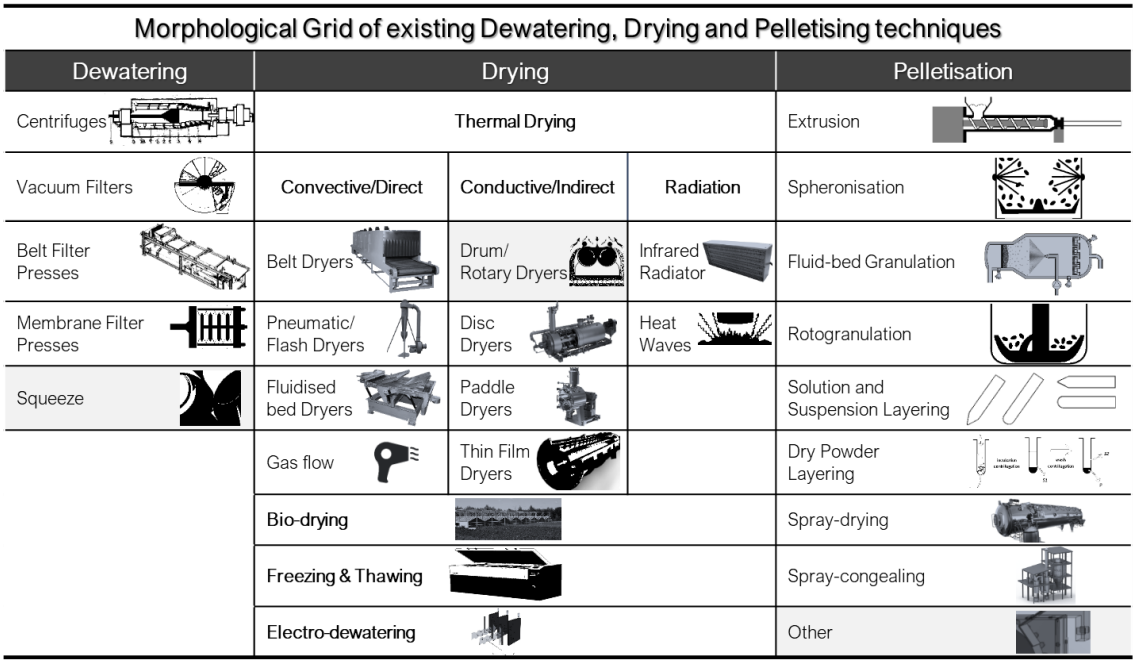

Figure 17. The morphological grid regarding the three main sub-functions (dewatering – drying – pelletisation). In light grey: the options selected.

The advantages of adopting a more holistic approach to the problem were now apparent to the design team. Using the same conceptual design to perform all the sub-functions

required would be favoured, as it would remove the complexities of combining multiple assemblies and would require less space inside the toilet.

3.4.5 Rapid prototyping

The idea of early-stage, rapid prototyping is to 'fail quickly, learn fast'. It aims to provide the designers with practical insights, which will then enable them to reject, sooner rather than later, concepts that do not work. It also helps identify problems and potential solutions for each prototyped concept. This is why very basic and low-cost materials were used for the rapid prototyping stage of the design process. Such materials included tin cans, wood, plastic, Meccano parts, screws, nuts and bolts.

According to experiments performed at previous stages, using a metallic surface would be beneficial and convective heating was considered more efficient in terms of time and moisture loss. Therefore, the idea of using a metallic drum with a scraper to create a continuous, but simplistic, conveyor type system came up (Figure 18a). In order to compress the sludge, the concept was soon converted into a two-drum design (Figure 18b). The device should be able to apply pressure to the sludge in order to dewater it. Like this, the stickiness of faecal sludge would be used for the dryer's benefit, as it would enable the system to dry the sludge which was stuck on the drums, using the heat coming from the bottom of the chamber. Then, the dried flocs would be scraped off, whilst the water produced during the dewatering and drying stages would be gathered using a channel placed at a lower level and in between the rollers. An important observation concerned the position of the scrapers. Whereas in the initial design the scrapers were positioned below the drums, it was found that if they were moved to the top, this would create a much larger drying surface. Finally, another key finding from the rapid prototyping stage was that an enclosure would increase the efficiency of the system, as it would be capable of retaining the temperature.

Figure 18. From left to right: **a)** Single drum concept, **b)** Double-drum concept, **c)** Low-fidelity prototype

Based on the observations from the previous stages, a new prototype started being built. Once again, the various versions of the prototype consisted of low-cost materials that could be easily found and modified, as there were still many issues to be resolved. The ultimate goal for this prototype was to embody all the principles that had been proven useful, but to also be robust enough for further testing.

Figure 18c illustrates a version of the prototype, made of tins and Meccano joints. Despite the simplicity of its materials, the prototype would prove itself really useful as it enabled the team, not only to make important corrections in the design, but to also prove that the concept had a lot of potential.

At this stage, a series of tests were performed to get an indication of whether the prototype was a move to the right direction or not. The tests showed that the desired moisture content could be achieved within half an hour of drying, at a temperature higher than 105°C. Thus, the concept was considered as proven and the green light for further development was given.

The drying system concept had now to be refined, incorporating the learnings form the testing phase. Furthermore, the next version should entail a more integrated design, suitable for testing in a harsher environment and capable of satisfying many of the manufacturing requirements, such as cost, manufacturability, robustness and easiness to assemble and to operate.

As a next step, the main findings that resulted from the preceded stages were analysed in order to come up with a first redesigned version of the dryer, resting on the aforementioned considerations. When the first refined design was concluded, many more followed, each one corresponding to a different challenge or criterion. A few examples of studied designs are illustrated in Figure 19.

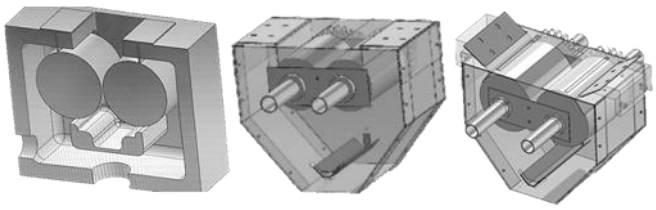

Figure 19. Examples of CAD designs for the dryer

For the surrounding cover used to retain heat, the concept of a thin stainless-steel frame was selected. Stainless steel was chosen as it constitutes a tough, heat conductive and corrosion resistant material with high temperature strength properties. A circular frame such as the one used for the proof-of-concept prototype could not be used, as the cost of steel casting would be extremely high. Except for being effective and efficient, the dryer had to be easily manufactured at a realistic cost. Hence, an assembly of stainless-steel sheets that could be cut and folded was preferred. Another feature of the selected design was that it could accommodate two drum sizes, which could be fitted into the dryer. Finally, the distance between the drums could be also adjusted between 1.5mm and 4mm. These design characteristics would allow the dryer team to test various options, using the same prototype. This in turn, means that the prototyping cost were kept at low levels and that the independent variables referring to the interior of the dryer would be fixed for all the tests.

3.5 Finalising conceptual design

In parallel with the rapid prototyping stage and before finalising the design, five testing periods lasting one to days each were performed to make sure that the prototype was functioning the way it was supposed to. From these tests, a series of problems were identified, and minor design changes were implemented to solve them. Table 2 summarises the key modifications.

Table 2. Problems identified in the first version of the Proof-of-Concept prototype

Problem Identified	Implemented Solution
The dryer required a long pre-heating period	The solid drums were converted into hollow ones
The scrapers were too loose and thus, did not always scrape the sludge off properly	A suspension system was added, using a set of springs and a couple of wedges
The steam of hot air was not properly directed to the drums	The water channel was modified
The scrapers should be adjusted from outside	The suspension system was redesigned so that it could be accessed externally

The surface tensions led the water towards the side walls	A couple of water channels were added at the bottom of the system
If the moisture content of the sludge was too high, the sludge could not be retained on the drums	The drums rotation speed was reduced
Small sludge bits build up in the water channel	A slight slope was added to the water channel

In total, about ten main prototypes were built until a satisfactory performance was achieved. Figure 20 illustrates all the different variations of the dryer prototypes from the early development stage until its current phase, which corresponds to a TRL 3. An important note that has to be highlighted, is that the design refinement process was a long-lasting one, and that all the prototyped versions relied on practical insights obtained from making, assembling and testing each prototype. These practical insights were crucial and played a decisive role in finalising each design and fixing the problems that occurred throughout the process.

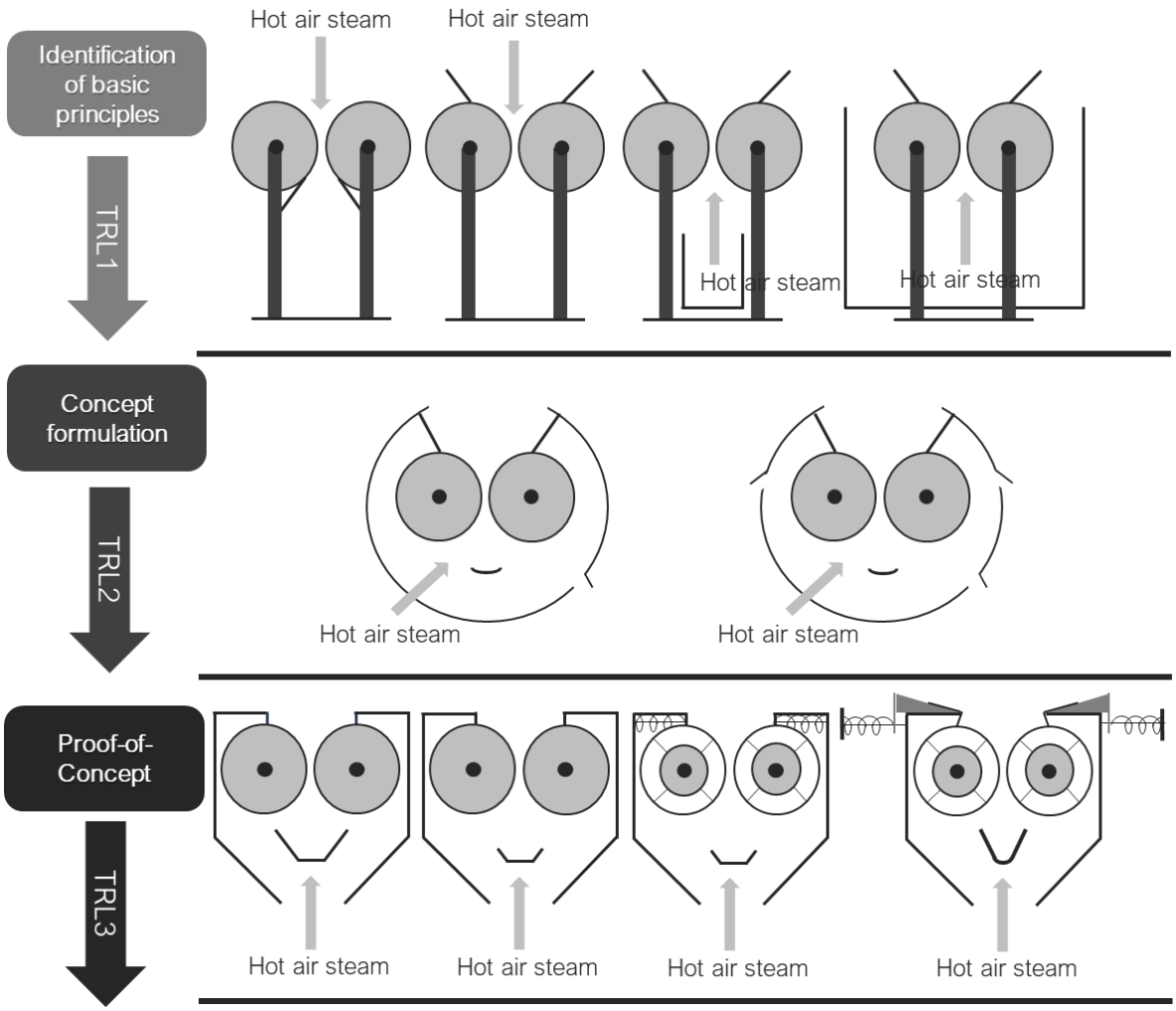

Figure 20. The evolution of the dryer prototypes

The technical drawing of the final dryer design, as this resulted from the aforementioned stages is shown in Figure 21.

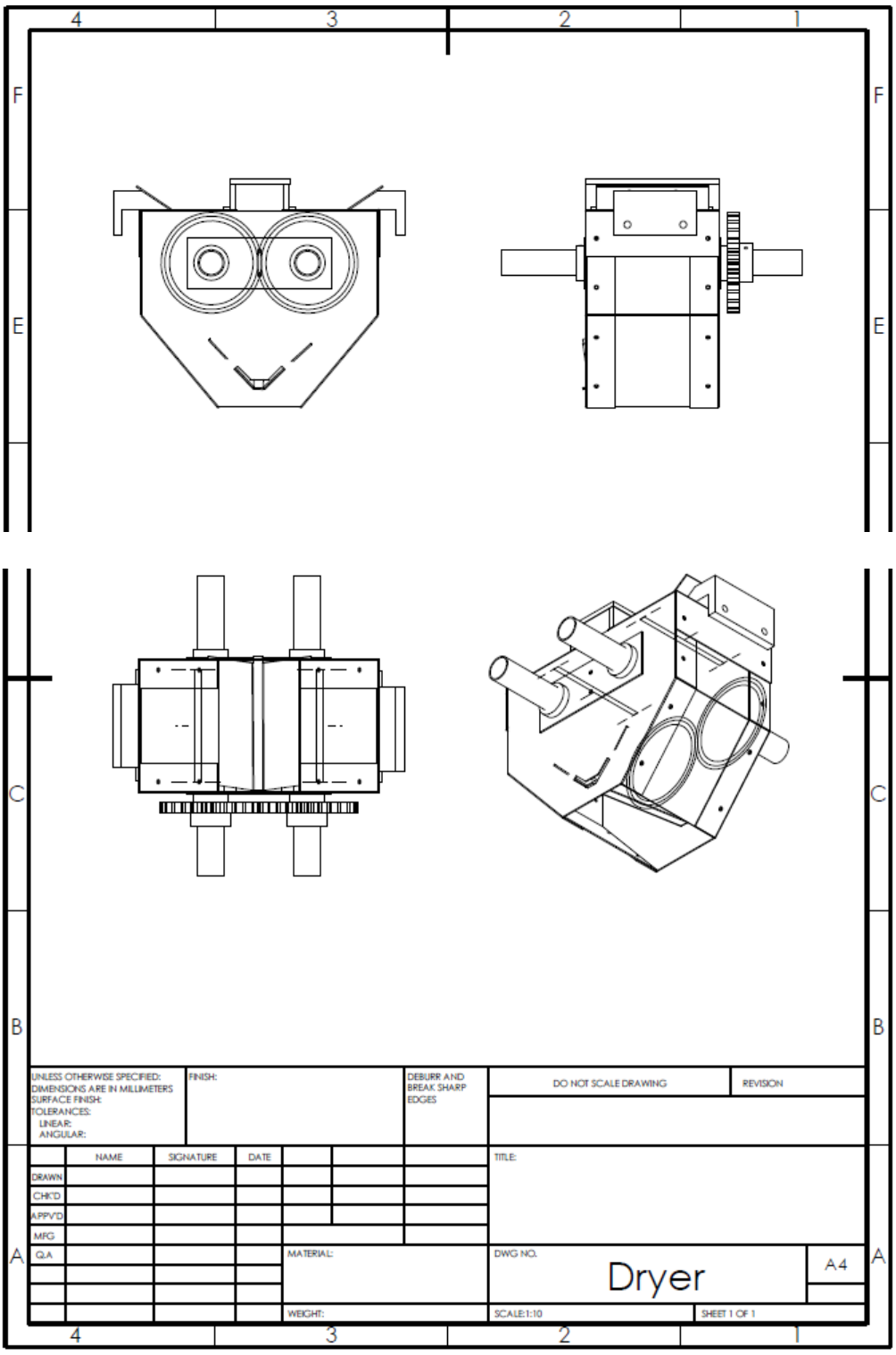

Figure 21. The technical drawing corresponding to the proof-of-concept version of the dryer

As happened with every prototype, drying experiments were performed using simulants (‘synthetic sludge’) to validate the latest one. Each test was repeated five times using

identical samples and under the same conditions. The quantitative, dependent variable examined was the moisture content of the sludge after certain periods of drying time. The qualitative variables observed were the functionality of the key parts of the prototype (drums, scrapers, liquids channel). For this test, a simulant consisted of water, yeast, psyllium, peanut oil, miso, polyethylene glycol, inorganic calcium phosphate and cellulose was used. The simulant recipe was selected sot that its density and stickiness properties were as close to the ones of real faeces as possible. Initially, two different temperatures were examined to test the impact that temperature has on the system, while the air flow rate and pressure were constant: 140 and 181° C. The tests were performed with ambient air moisture content and the inlet volumetric flow rate was 300lpm. The dried samples were collected at frequent intervals. Following the drying procedure, the samples had to be placed in the oven for 24 hours at 105°C. Their weight was measured before and after the drying process, using a high-accuracy scale to calculate their final moisture content. The results are presented in Figure 22.

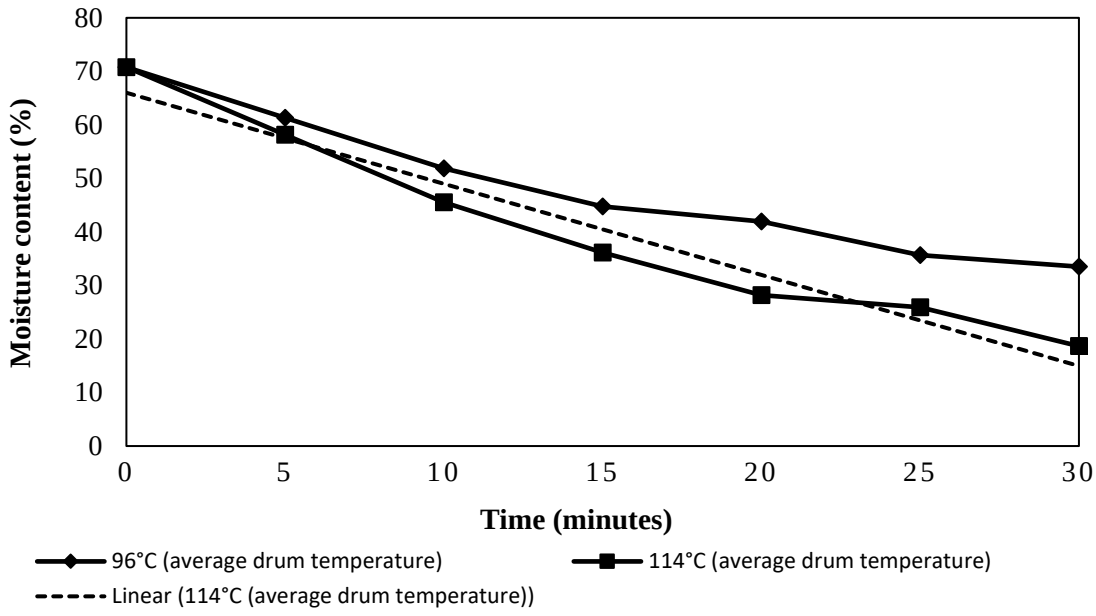

Figure 22. The evolution of the dryer prototypes

The conclusions from the testing stage clearly showed that the system could deliver what is expected from it, should the conditions be right. They also provided the dryer team with valuable information concerning the limitations of the dryer regarding the minimum

moisture content it can accept as an input and the range of air flow rates, pressures and temperatures in which the system can operate.

3.6 Key findings from chapter 3

The dryer designed and developed in the context of the of the 'reinvent the toilet' project of Bill and Melinda Gates Foundation, is presented as an example of complex challenge encountered by the team that designed it. The design process led to a TRL 3 prototype within almost a year since the beginning of the project. The proof-of-system prototype, at its latest version, seems to meet several requirements from the specification document and further testing is needed to define the exact number.

There are several limitations that need to be acknowledged regarding the design stages of the dryer concept. An important limitation is related to the complex testing procedures required. Many testing rigs are still in the development phase, as they require very precise equipment to acquire measurement data. In fact, often each test involves different procedures and equipment, depending on the dependent and independent variables examined each time.

A key challenge which has yet to be resolved concerns the energisation of the moving parts of the dryer. As the scope of a powerless toilet is restrictive in terms of the use of external power sources, a system to drive the moving parts is being designed. An additional procedure is also needed to convert the dried flocs into combustible masses of around 1g each. A technology suitable to serve this purpose has been designed and is about to be prototyped in the near future. Both additional technologies will be positioned around the dryer, in a way that the system's restrictions in terms of space are satisfied.

There are still detailed, scientific tests going on to help the dryer team define the exact capabilities and limitations of the dryer and how these can be further improved. The purpose of this paper is not to enclose all the scientific information that come from these processes, but to present in a concise way the design process of this novel technology up to its current readiness level.

An essential goal of the present chapter is to demonstrate the value of the designed novel technology and of course, that of the findings that came along with it, which can be of high significance to scientific or R&D teams working on water and sanitation projects.

But through this case study, it also communicates the main stages of the design process when developing a new technology. The case of the dryer design is indicative of the way that designers work when facing a complex problem. Complexity is linked to ill-structuredness, that is, a situation where the structure of the problem and the information about it are unclear (Churchman 1967; Simon 2012). This case can be considered as a complex problem one, as it meets three criteria: it entails ambiguous specifications of goals, has no pre-determined solution path and requires the integration of multiple knowledge domains, such as process engineering, chemistry, mechanical engineering and industrial design (Simon 1973).

3.7 Summary and next steps

This chapter reviews the design and development of a drying device, which is part of Cranfield University's self-sustained and waterless toilet. Each stage of the process is being thoroughly presented and explained, by giving prominence to the steps, logic and methodology of the design team. The design and development journey resemble to a sequence of problem-identification and problem-solving procedures, where both the analytical and the holistic approaches are crucial. This case study, being indicative of a typical design process, can be used to demonstrate the steps followed by designers when they encounter complex challenges in the context of activities, which concern the invention of new technologies.

The findings indicate that the designed, under development technology is moving to the right direction, since it can already meet most of its essential objectives, as they were set by the initial scope and described in the specification document.

The next step is to test the system further to define how air flow rate and pressure affect the drying process at certain temperatures and to validate the concept already described in this chapter. These tests are presented and analysed in the following chapter.

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4 PERFORMANCE EVALUATION OF A NOVEL DOUBLE-DRUM DRYER

Objective 3: Test and validate the novel technology developed in the context of the study

Chapter 3 presented the conceptual design stages of a double-drum dryer that was developed at Cranfield University, in the context of the 'reinvent the toilet' challenge set by the Water, Sanitation & Hygiene programme of the Bill & Melinda Gates Foundation. The purpose of the present chapter is to assess the novel dryer's performance, to explore its potential capabilities and weaknesses and to define how many functional requirements it meets.

Keywords for this chapter: *double-drum dryer, performance evaluation, technology testing*

4.1 About drum dryers

Drum dryers are used to dry a variety of foodstuffs and chemicals. A non-exhaustive list of materials for which drum dryers are used includes cereals, soup mixtures, yeast creams, fruit purees, starches, polyacrylamides, sodium benzoate, propionates, acetates, sludge and paste of varying viscosities (Bonaui et al. 1996; Islam et al. 2007; Mujumdar 2014). They are generally considered as an agile (as they can treat a wide range of products), cost-effective and efficient operation, which leads to higher production rate and reduces labour requirements (Mujumdar 2014).

Double drum dryers consist of two cylindrical tubes (drums) of the same diameter, rotating in opposite directions. The drums are placed very close to each to other, but the exact gap might vary from one dryer to another. The drums' rotation speed is regulated by a conveyor-type system, usually a pair of belts.

Usually drum dryers are used as conductive dryers, meaning that the heat is transferred through the drum surface to the liquid paste, causing it to form a viscoelastic fluid with particularly sticky properties. The material entering the double drum dryer first forms a 'pool' of sludge between the drums. In the case of starch, this is the moment when its intermolecular bonds are broken down, forcing the liquid to thicken. This part of the

procedure is referred to as ‘gelatinisation’. The actual drying process begins only after the gelatinised material leaves the pool, forming a thin film upon the surface of the drums. The film thickness is dictated by the gap in between the drums. The smaller the gap, the thinner the film is and therefore more heat or drying time is required for it to reach the desired moisture content. Also, a smaller gap reduces the possibility for the material to fall through it. An extensive study on the effect of the drum surface temperature and width of the gap between the drums on the output has been conducted by Vallous et al. (2002). This study confirmed that the product film’s thickness is determined only by the drum gap width and that the higher the pool’s level, the lower the temperature of the drums’ surface gets.

There is a vast literature regarding the operational and performance characteristics of drum dryers, especially for the ones used for industrial applications. Gardner (1971) presented a complete review of operational features for a wide range of drum dryers. In whatever concerns drum drying of products with high moisture content, i.e. ≃80% w/w, it has been investigated by a series of systematic studies conducted by Vasseur and colleagues (Vasseut and Loncin 1983; Abchir et al. 1988; Trystram et al. 1982; Trystram et al. 1988; Vasseur et al. 1991a, 1991b; Bonaui et al. 1996; Rodriguez et al. 1996a, 1996b). These studies were the first ones to show that in drum drying, the most prominent drying phenomenon that occurs is boiling, at least in the initial stages, where the majority of heat is exchanged.

Despite the research studies on drum drying, the ones on double drum dryer in particular, are limited and they focus mainly on technological aspects (Kalogianni et al. 2002). Hence, it has to be noted that there are significant differences between single and double drum dryers and therefore direct comparisons cannot be made. For example, in single drum dryers mass flow rate and film thickness depend very little on steam pressure, whilst in double drum dryers steam pressure plays a prominent role in the identification of the gap width (Gardner 1971).

According to Gavrielidou and colleagues (2002), there are five variables affecting the operation of a double drum dryer:

1. Steam pressure
2. Rotation speed

3. Gap between the drums
4. Pool level
5. Physical properties and temperature of feed material, when the latter reaches the drum surface

4.2 Method and apparatus

The sludge used to evaluate the dryer's performance consisted of commercial miso containing around 50% water basis moisture content, water and psyllium. The recipe was as follows: 200ml water, 600g miso, 3g psyllium. The psyllium was used as binding agent to make the mixture slightly thicker. Mixture samples were fully dried in the oven at 105˚C for 24 hours to define the mixture's moisture content based on Equation 8, where M_w is the moisture lost in the oven and hence, the initial moisture content of the sample. $M_{crucible}$ is the mass of the crucible, $M_{initial}$ stands for the combined mass of the sample and crucible before drying and M_{final} is the corresponding mass after drying:

$$M_w(\%) = \frac{(M_{initial} - M_{crucible}) - (M_{final} - M_{crucible})}{(M_{initial} - M_{crucible})} \quad \textbf{(Eq. 8)}$$

Following the above method, the average (wet basis) moisture content of the sludge samples was estimated as 71.67%. The feed material was at ambient temperature when reaching the drum surface.

The proof-of-concept prototype, the evolution of which was presented in chapter 4, resulted by integrating all the sub-concepts designed and modified throughout the design and development journey. The prototype's robustness was the main consideration, making sure that it would be sufficient for the testing procedures that would follow. The purpose of the testing phase was to answer the following question regarding the newly designed dryer:

Q1. Does the dryer work? If yes, up to what extend (against the original scope) and how efficiently?

This question can be further broken down to the following three sub-questions:

Q1A: Does the dryer dewater (remove unbound moisture)?

Q1B: Does the dryer dry (remove bound moisture)?

Q1C: Does the dryer perform the aforementioned tasks efficiently?

Q1A and Q1B concern the efficacy of the technology (‘does it do what it is supposed to?’), whilst the Q1C refers to its efficiency (‘how well does it do it and how can it be improved?’). In order to address these questions a suitable methodology was developed. The dryer’s testing procedure was divided into three main stages: a) the estimation of its dewatering capacity, b) the identification of the optimal air flow rate and temperature within the existing system constraints, c) the identification of heat losses and d) the estimation of its drying capacity. Soon after, a physical rig began being constructed. The testing rig that was designed consisted of the following components:

• A source and a line of compressed air
• A pressure gauge to adjust pressure
• An air flow regulator to dictate (volumetric) air flow rate
• An AHP-7562 Omega Air Heater
• A Eurotherm 2216e PID temperature controller to control the air heater so that the latter provides the desired temperature
• K-type probe, 480˚C rated, 1m lead to feed the PID controller with actual temperature measurements
• Polyurethane tubing 8mm diameter for the compressed air line and all interconnections between the rig’s sub-systems
• The dryer prototype
• 5 K-type thermocouples placed inside the dryer to measure the temperature where needed (3 in different positions around the drums, 1 at the air inlet point of the dryer at the bottom, 1 at the outlet point of the dryer at the top)

Additional consideration was needed to address health and safety issues that would derive from this testing procedure. As the temperature that would be used to test the dryer would not be as high as the one used by the combustor (~600˚C), literature evidence showed that possibly biohazardous aerosols would be released. As a result, a local exhaust ventilation unit (LEV) was made especially for the testing rig of the dryer.

The experimental diagram of the testing rig is depicted in Figure 23, whilst Figure 24 shows a picture of the actual rig in the lab environment where it was tested.

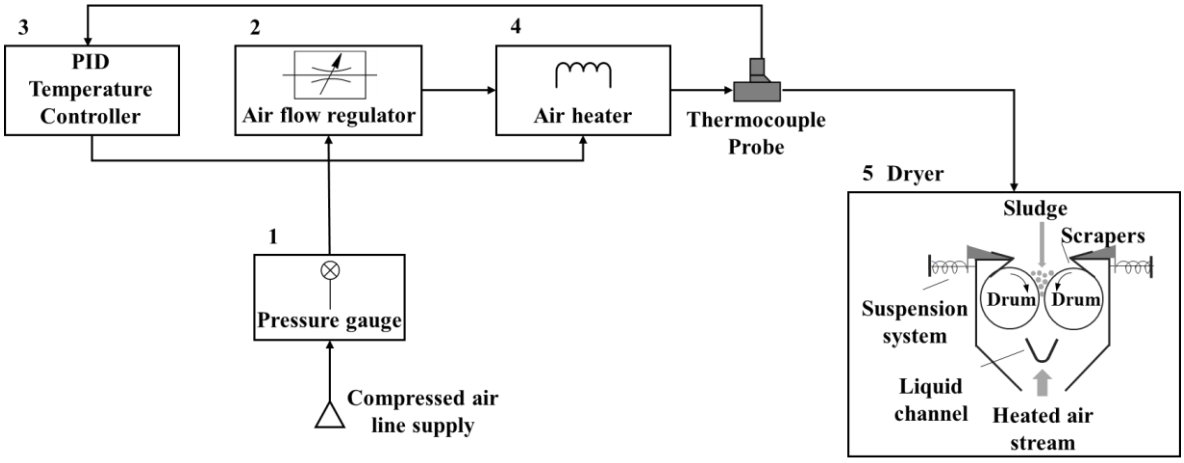

Figure 23. Schematic diagram of the experimental apparatus

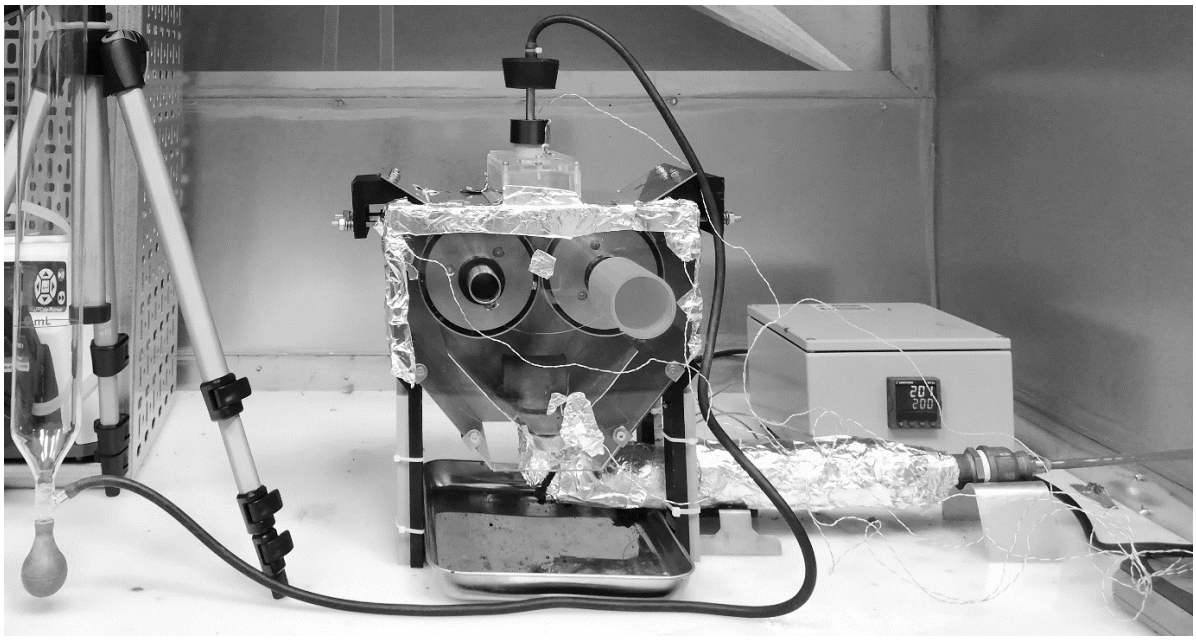

Figure 24. A picture of the actual testing rig inside the LEV unit. The dryer prototype (in the middle), the air heater (the foil-wrapped pipe at the bottom of the dryer) and the PID controller (the box with the digital display at the back right of the chamber)

The temperature inside the dryer was recorded using 5 K-type thermocouples placed at the positions described above. The drums were manually, but synchronously driven, at a set of low speeds ranging from 0.2 to 0.017rpm, using a gearing system. Unlike typical industrial dryers where drums rotate at higher speeds and the scrapers are activated once every few rotations, in this case the scrapers were fixed at the specific position, tangent to the drums.

4.3 Results and discussion

4.3.1 Effect of pressure on average drum temperature

The theory had clearly indicated that the higher the mass flow rate, the higher the drying capacity of the dryer would be. With the setup described above, there was not an easy way to directly measure and regulate mass flow rate. Knowing though, that is a direct correlation between mass flow rate and volumetric flow rate, the control of the latter was selected as a first step to move forward with the existing means at the time. This decision was also informed by knowledge of equipment and means to measure mass flow rate which follow exactly the same process, but they do it in a concise way. Of course, such a piece of equipment would require resources (cost, time and know-how) that did not exist at the point when the tests were executed.

Information was requested by the combustor R&D team on what the estimated volumetric flow rate, pressure and temperature of the exhaust would be. The answers provided, mentioned a range of what seemed to be realistic for the combustor and included an air flow rate of up to 24lpm (litres per minute), a mean temperature that ideally would not exceed 100°C and an air pressure as close to ambient as possible.

As a first step, a series of volumetric flow rates from 4lpm up to 24lpm were examined and assessed versus the average drum temperature inside the chamber. The air flow rates were applied in incremental steps of 2lpm, with the step from 17lpm to 20lpm being the only exception. The inlet air temperature was selected based on previous insights to be 200°C and, for this particular test, it was taken as an independent (non-examined) variable. A remaining independent variable that had to be define before testing was air pressure. To do this in a simple way, two different pressures with a significant gap between each other were tested for two selected air flow rates. More precisely, 0.5bar and 5bar were examined in terms of impact on the average drum temperature for a pair of volumetric air flow rates: 4lpm and 6lpm respectively. The results are shown in Figure 25.

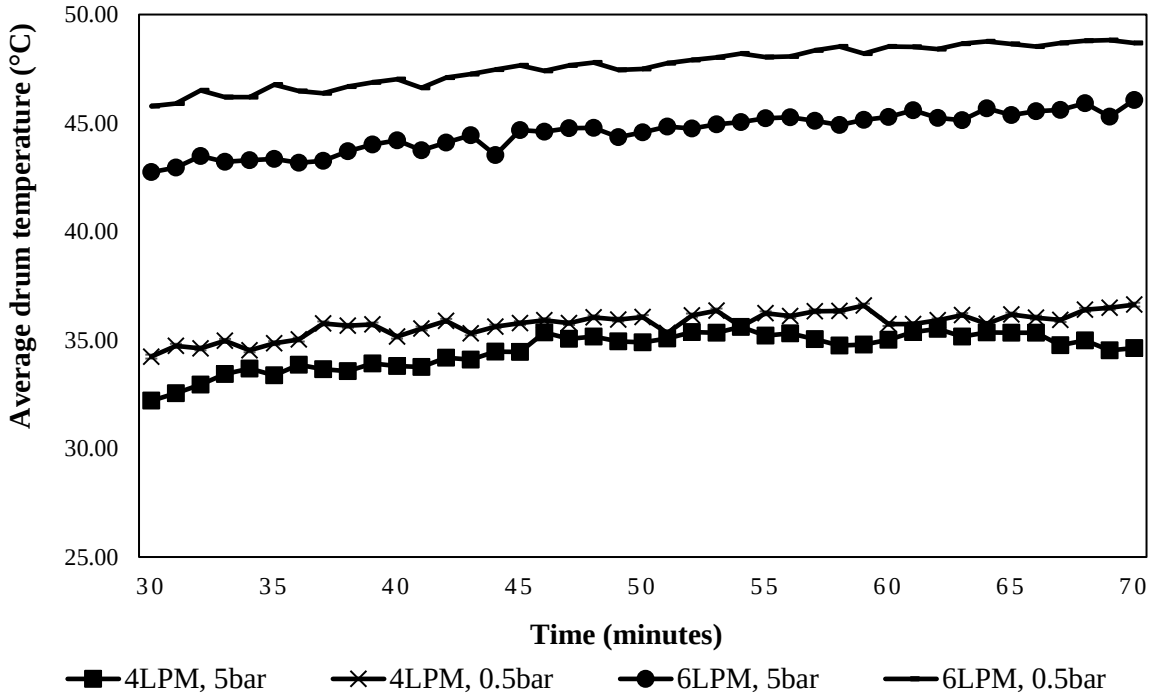

Figure 25. Average drum temperature versus air flow rate for 0.5bar and 5bar air pressure

Despite the theoretical predictions, the results showed the lower pressure resulted to higher drum temperatures for both air flow rates tested. A possible explanation given to this anomaly is related to the fact that higher steam pressure leads to higher drum temperature derives from conductive double drum dryers (Gavrielidou et al. 2002), where the steam flows from the inner side of the drums. In this case, the main source of heat is convective. A change into a conductive double drum dryer will probably result into a better exploitation of the steam's thermal power and ultimately into an increase of the overall efficiency of the dryer.

Following the above findings, a decision was made to set 0.5bar as the nominal pressure required for the dryer's inlet air. This pressure, being close to ambient, would facilitate the requirements regarding the combustor to be achieved without the need of excess devices to increase air pressure, e.g. pumping units.

4.3.2 Effect of volumetric flow rate on average drum temperature

In order to assess the impact of air flow rate on drum temperature, three K-type thermocouples were recording temperature on three different positions around the drum surface. The other two thermocouples were recording the air temperature at the inlet and

outlet positions of the dryer. Afterwards, the average drum temperature was calculated. The actual results shown in Figure 26 confirmed the theoretical hypothesis that the higher the volumetric flow rate, the higher the average drum temperature and therefore, the higher the drying capacity would be.

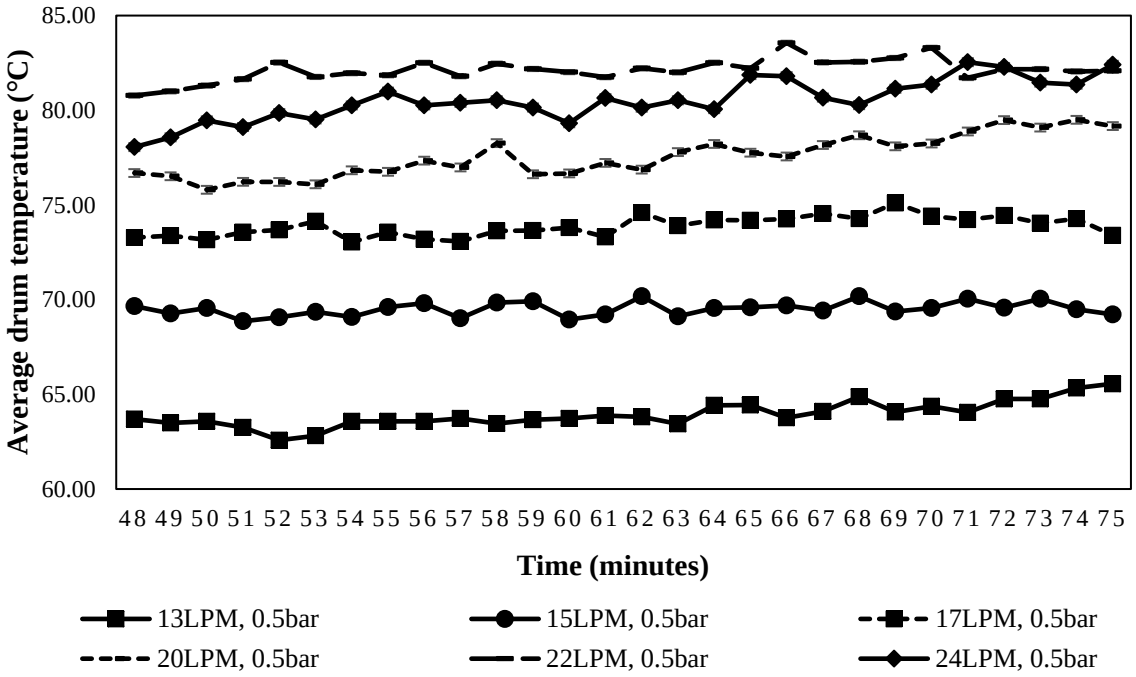

Figure 26. Average drum temperature over time for various air flow rates and a constant supply of 200°C steam

Another useful observation was also noticed. The higher the air flow rate, the smaller the difference between the measured average drum temperature and the one corresponding to the immediately lower air flow rate would be. More precisely, a minor -rather than a significant- difference in terms of average drum temperature was noticed in between 22lpm and 24lpm. Thus, and in order not to stretch the combustor's capabilities, it was decided to select 22lpm as the preferred nominal volumetric flow rate for the dryer's input.

4.3.3 Heat losses inside the drying chamber

As a next step, and based on the selected volumetric air flow rate and pressure, the heat losses inside the drying chamber were calculated. This would not only shed light on the dryer's efficiency, but it would also enable the definition of the temperature range which

would be required to reach the desired temperature around the drums (~100°C as it was set during the preliminary stages of the dryer design).

Based on calculations related to the minimal, average and maximum air temperature that could be retrieved by the combustor's exhaust outlet, a temperature of 200°C was considered as a fair estimate for the dryer, but also a possibly achievable one for the combustor. For a fixed air flow rate of 22lpm and varying inlet air temperature, the average drum temperature was recorded as shown in Figure 27. The theoretical hypothesis that higher inlet temperature would lead to higher average drum temperature was obviously confirmed, so the main focus of this test was to record the temperature difference. This would not only help identify the performance of the dryer in terms of heat losses and efficiency, but it would also be used as a reference point for when the same process, for exactly the same independent variables would be repeated, this time with material to be dried. Moreover, the results, even without further analysis would be able to answer whether for the selected inlet air flow rate, temperature and pressure, the average drum temperature would meet the standard set by the theoretical hypothesis as required, i.e. 100°C. Figure 27 clearly shows that the average drum temperature reached about 85°C for the highest temperature tested, and thus did not meet this standard. The results also confirmed that the losses in the tested, early-stage prototype are quite significant, as it is not sealed and insulated properly.

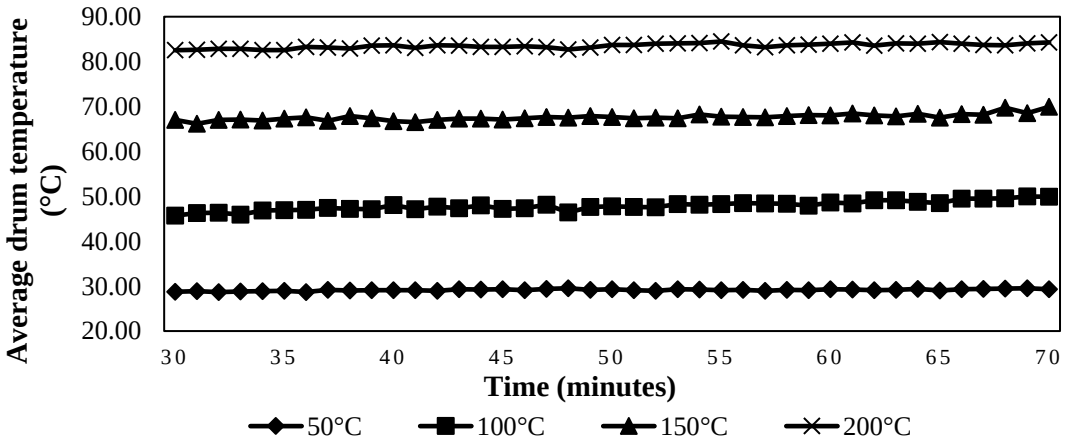

Figure 27. Average drum temperature over time when the dryer is not loaded with sludge

The above results were then compared to the corresponding losses for the same input and conditions when the dryer was loaded with sludge to dry. This comparison was attempted

for the following temperatures: 50°C, 100°C, 150°C, 200°C and the results are presented in Table 3. The sludge's moisture content, expressed in g/100g water basis terms, was calculated as described in the method section. The specific load of the drums was calculated based on the drums' surface area, estimated equal to 0.078519m^2 (in total, for both drums).

Table 3. Effect of pressure on drum temperatures for a constant supply of 200˚C steam

50°C				
	Both drums No sludge	**Both drums** With sludge	**Air outlet** No sludge	**Air outlet** With sludge
Mean temperature (°C)	28.93	26.76	23.32	23.70
Sludge moisture (g/100g w.b.)	-	71.67	-	71.67
Product flow rate (kg/h)	-	70×10^{-3}	-	70×10^{-3}
Specific load (kg/m^2)	-	0.45	-	0.45
100°C				
	Both drums No sludge	**Both drums** With sludge	**Air outlet** No sludge	**Air outlet** With sludge
Mean temperature (°C)	45.35	41.89	34.42	34.25
Sludge moisture (g/100g w.b.)	-	71.67	-	71.67
Product flow rate (kg/h)	-	70×10^{-3}	-	70×10^{-3}
Specific load (kg/m^2)	-	0.45	-	0.45
150°C				
	Both drums No sludge	**Both drums** With sludge	**Air outlet** No sludge	**Air outlet** With sludge
Mean temperature (°C)	66.69	53.75	50.71	40.85
Sludge moisture (g/100g w.b.)	-	71.67	-	71.67
Product flow rate (kg/h)	-	70×10^{-3}	-	70×10^{-3}
Specific load (kg/m^2)	-	0.45	-	0.45
200°C				
	Both drums No sludge	**Both drums** With sludge	**Outlet** No sludge	**Outlet** With sludge
Mean temperature (°C)	82.36	70.55	64.92	49.21
Sludge moisture	-	71.67	-	71.67

(g/100g w.b.)				
Product flow rate (kg/h)	-	70×10^{-3}	-	70×10^{-3}
Specific load (kg/m^2)	-	0.45	-	0.45

At a very high level, it can be observed that as drying temperature grows, the difference between load and no-load average drum temperature also increases. That means that for higher inlet temperatures, the sludge tends to absorb more heat and thus to naturally to dry faster. As expected, 200°C is the temperature that leads to better performance, even though the average drum temperature does not reach the required levels (i.e. ~105°C). Figure 28 presents the comparison results summarised in Table 3, only for the selected inlet temperature.

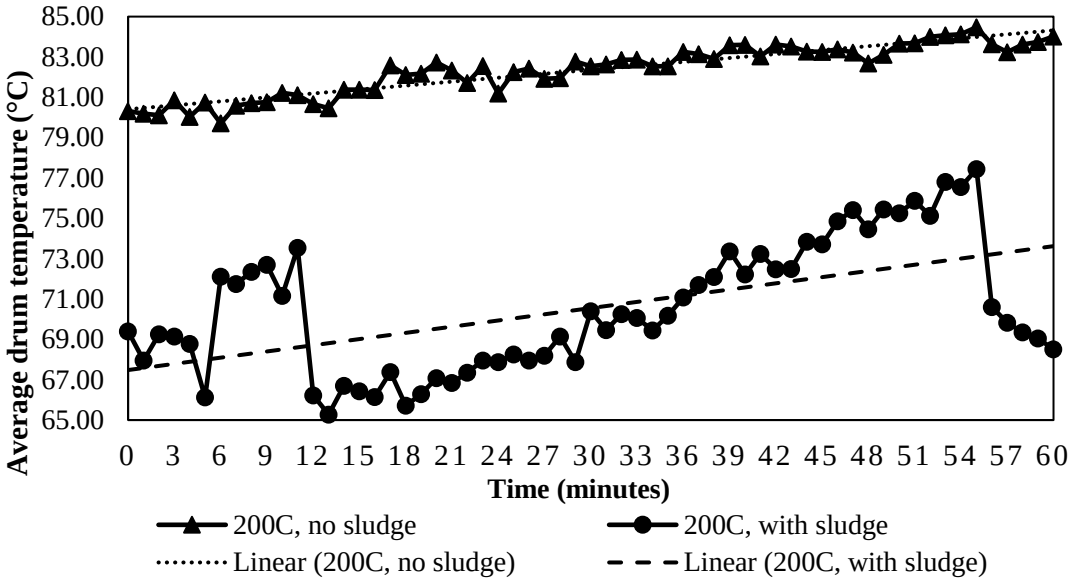

Figure 28. Average drum temperature over time at 200°C inlet temperature, with and without sludge load

This first series of tests might have not helped answer any of the questions Q1A-Q1B, but in reality, they were very important a) to define the independent variables for the upcoming tests what will directly answer the questions and b) to provide necessary data to answer question Q1C.

To summarise the findings up to this point, the hypothesis that higher temperature and air flow rate would lead to better performance in terms of average drum temperature, were confirmed. However, as the difference between 22lpm and 24lpm was not significant, the

lower flow rate was selected, as it would increase the chances of complying with the external system constraints. Out of all the inlet temperatures tested, the highest one (200°C) led to best performance. Even at this highest inlet temperature though, the average drum temperature did not reach 105°C, which was the initial requirement set during the design process. Moreover, this difference of about 115°C (between 200°C and 85°C) implies the improvements that need to be made in the next versions of the dryer regarding the insulation and the overall thermal efficiency of the system.

4.3.4 Drying kinetic curve

Now that some of the testing independent variables were defined, the drying performance of the dryer could be defined. In order to construct the drying kinetic curve for the dryer, faeces simulant ('synthetic sludge') was used. The selected simulant does not differ much from the recipe that recent studies have recommended to make synthetic sludge (Penn et al. 2018). The simulant selected consisted of miso, water and psyllium, as it was found that its physical properties (mainly stickiness and density) were closer to the ones of real faeces. The moisture content of the sludge was measured to be equivalent to 70 wt. %. The dependent variable examined this time was the moisture content of the sludge after certain periods of drying time. Apart from the main dependent variable, some qualitative variables related to the operational functionality of the dryer would be also examined. Examples of such variables would be the efficiency of the gearing system assigned to rotate the drums, the scrapers and the liquid channel. The tests were performed with the parameters defined above: ambient air moisture content, inlet volumetric flow rate of 22lpm, pressure 0.5bar and 200°C for the air temperature at the inlet point of the dryer.

The synthetic sludge was fed into the dryer in bunches of 35g, which is the maximum amount of sludge that the dryer is currently able to process per cycle. Sludge samples were collected at 5-minute intervals starting from 0 and going up to 60 minutes of drying time. At each interval, all the sludge that had been previously fed into the dryer was scraped off to make sure that the residual sludge would not affect the quality of the upcoming samples. Following the drying process, the samples were placed in the oven for 24 hours at 105°C, following the same moisture content measuring method described in section 5.2. Their weight was measured before and after the drying process, using a

high-accuracy scale to calculate their final moisture content. The results are presented in the graph shown in Figure 29.

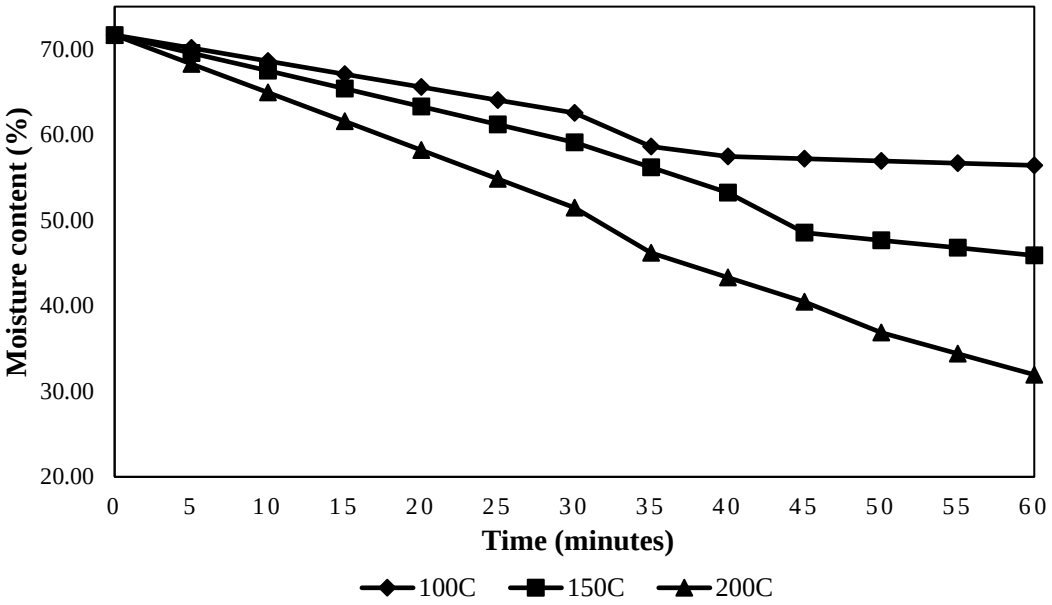

Figure 29. Kinetic curve of moisture content per drying time

The samples as they resulted from the dewatering-drying and pelletising process at the various drying intervals (i.e. 0', 30', 35', 40', 45', 50', 55', 60') are shown in Figure 30. The difference between the first (0') and the last (60') regarding their physical properties is obvious even visually. Another conclusion that draws from the sight of the dried samples is that the drier samples are larger in terms of volume, e.g. the sample corresponding to 30 minutes of drying time is smaller than the one that derived after 35 minutes, etc. The reason for this, is that the higher the moisture content of the sample, the more difficult it is to scrape it off.

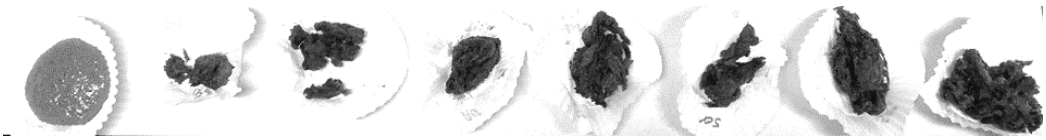

Figure 30. From left to right: samples of simulant sludge after **a)** 0, **b)** 30, **c)** 35, **d)** 40, **e)** 45, **f)** 50, **g)** 55, **h)** 60 minutes of drying

Drier samples are generally easier to acquire from the dryer, whilst samples belonging to the pitting stage (as explained in chapter 4) tend to be sticky and therefore more difficult

to be scraped off using the blades. What tends to happen with this sludge is that it starts gathering around the scrapers

According to the aforementioned results, the dryer can achieve a moisture content of about 30 wt. % within 60 minutes of drying, at a flow rate of 22lpm and an inlet temperature of 200°C. Although there is still distance to be covered, these results are close to the desired ones (20 wt. %) and it is hoped that the implementation of certain design improvements, the heat losses will be reduced significantly, and the dryer's efficiency will be improved drastically. The ultimate goal is to achieve 20 wt. % within almost 30 minutes of drying time; a benchmark that has been achieved with the current design (both with simulant and faecal sludge), but at a higher air flow rate.

4.4 Key findings from chapter 4

The results from the dryer testing revealed the dryer's proof-of-concept prototype's capabilities. More precisely, they showed that with the current system boundaries (volumetric air flow rate of 22lpm, 200°C inlet temperature and almost ambient pressure), the dryer can achieve, at its best a moisture content, of 30 wt. % from about 70 wt. % within 60 minutes of drying time.

This reduced efficiency is highly linked to the lack of insulation, the fact the prototype was open from both ends (air inlet-bottom and outlet-top). Its performance though, proved -at a large extent- the concept and provided enough evidence to believe that when the implementation of certain design improvements takes place, it will meet the essential objectives as these were described by the specification document (see chapter 3).

The questions raised in the beginning of the chapter, can now be answered as follows, based on the testing results:

Q1A: Does the dryer dewater (remove unbound moisture)?

- Yes, since the final moisture content is below the levels set as 'dewatering levels', i.e. <60% wb mc (see chapter 4). This does not mean that the liquid trapped in the channel, or the remaining water that runs through the drying chamber does not affect the thermodynamic behaviour and ultimately, the performance of the dryer.

Q1B: Does the dryer dry (remove bound moisture)?

- Yes, as it is clearly evidenced from the results that derived. In fact, it was first shown that the dryer dries. Again, this does not imply that the drying process is as efficient or fast as it should be. On the contrary, several design improvements need to be made in order to reach the levels of efficiency required to constitute the dryer a viable solution. However, since the essential objectives are met and for some of them, there is evidence that they can be met with certain improvements, the concept can be considered as proven.

Q1C: Does the dryer perform the aforementioned tasks efficiently?

- The heat losses and the temperature difference between the air supply and the dryer inlet point are indicating that the dryer's performance is not as efficient as it should be. This is the area where most of improvement is needed in order to proceed with this designed technology.

4.5 Summary and next steps

From the testing process of the dryer, the concept can be considered as proven, despite the improvements that are needed.

As a next step, the design process of the dryer as this was presented in chapter 4, is going to be analysed using design theory. This will evaluate the dryer as a product of the design process and will shed light on which element played a prominent role in its design. The goal is to understand which element is the one that facilitates the invention process, so that it can be isolated and further examined.

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5 REPRESENTING THE DESIGN OF A NOVEL TECHNOLOGY USING DESIGN THEORY

Objective 4: answer research question by applying design theory.

The double-drum dryer previously designed, built and tested, is now being represented from a design theory perspective. The present constitutes a core chapter of the study, as it brings together the theoretical findings from chapter 2 and the practical insights gathered from the case analysed in chapters 4 and 5. The main body of the work entailed in this chapter lies in the field of design theory and can be characterised as novel, since this is -arguably- the first study that uses the specific design theories, especially C-K, to reflect upon an ongoing design project.

The chapter is divided into two main parts: the first part analyses the dryer design using axiomatic design (AD), whilst the second relies on the C-K model. Each theory examines different aspects. AD focuses on the information and complexity axioms; it benchmarks the dryer against a theoretically 'optimal' design and attempts to define the system's complexity and therefore, its ergonomic efficiency. C-K on the other hand, is concerned with the design process rather than the resulted concept itself, focusing on the predominant design techniques applied in the early stages of the conceptual design. The two theories are used in combination, aiming to obtain a more holistic result from the performed analysis.

Keywords for this chapter: *design theory, case study evaluation, axiomatic design, C-K theory, design techniques*

5.1 Using design theory to reflect upon the design process of novel technologies

The dryer's design and development process were narrated in chapter 4, while chapter 5 presented its testing procedure and the data-driven conclusions that derived. At this point, after obtaining testing and validation results, any typical design journey would end. It is usually at this point that constructive feedback is provided to inform the process to either start all over again (when the design fails) or to terminate (when there are no more improvements to be implemented).

But this chapter is only signalling the beginning of the most crucial part of the study. The findings extracted by the two previous chapters of the case study will now be brought together with the two theories selected and analysed in chapter 2. The goal is to reveal the way that a novel technology, developed in the context of a global, high-profile project was designed, hoping that the insights will be able to be isolated and consolidated into transferrable knowledge and findings.

It is not the first time that design theory is applied to case studies for this purpose. Kroll and Farbman (2016) for example, applied a general conceptual design method called 'parameter analysis' (PA) to investigate four diverse, innovative case studies from the aerospace sector. They identified three common predetermined PA characteristics among all case studies. However, these characteristics (i.e. the three-step process, first principles and parameter identification) are quite generic and seem more like design principles rather than techniques. The authors claim that the pattern identified reveals the innovators' thought process, but in reality, a process is nothing more than a prescribed method, usually incapable of describing the 'creative leaps' or the underlying mechanisms that often take place. A study performed later by Weisbrod and Kroll (2018) introduced another prescriptive model, suitable for conceptual engineering design: idea-configuration-evaluation (ICE). ICE is a hybrid between PA and C-K, aiming to take advantage of the benefits deriving from both models. PA is formulated based on designers' insights and C-K has strong connections with logic theory. The paper was mainly focused on the demonstration of the model's capabilities to capture the dynamics and rationale of conceptual design.

For the examination of the dryer case study the following two theories were selected: C-K theory, created by Hatchuel and Weil (2003, 2009) and Suh's axiomatic theory (1998, 1999). C-K constitutes the latest and most widely acknowledged model regarding conceptual design amongst the design research community. Its deep foundations in logic theory along with its 'flexibility' that enables it to accommodate almost every act of design (even out of the strict boundaries of the design discipline) are partly the reasons for its growing popularity. Moreover, C-K is among the first design theories that somehow managed to capture some essential elements of the innovation process. In this particular case, C-K was selected in order to reveal the mechanisms that consciously

drove the design of the dryer. As a result, in the context of this study it is used more as a descriptive rather than as a prescriptive model.

On the other hand, axiomatic design theory (AD) has completely different characteristics. When it began being formulated, AD was mainly an application of linear algebra in design theory. Later on, the model embraced the theory of complexity, in an attempt, not necessarily to understand how designers deal with complexity, but how the complexity of a design affects its efficacy and efficiency. The latter was also the reason why the it was selected as a model to assess the dryer design. Complexity is an aspect that this study is very interested in, and AD is undoubtedly the only design model that includes it. In fact, not only it includes it, but more importantly, it translates it into something tangible that can be applied in any designed system.

To summarise, C-K theory is used to 'decode' the techniques and mechanisms until the generation of the final concept (corresponding to the proof-of-concept design), aiming at getting some insights regarding invention. AD is applied to capture core notions of the study, such as complexity, and translate them into tangible results. Last but not least, both theoretical models display an important advantage; they convert the notions they examine into quantitative and thus measurable variables; a feature not easily met in design research.

5.2 Using axiomatic design to assess the dryer's design

As discussed in chapter 2, axiomatic design (AD) has two main objectives. The first one is to prescribe criteria towards the development of the 'best' design, and the second one is to provide generic instructions for minimising the complexity of a designed system. The goal is to increase the robustness and reliability of the system by reducing its complexity (Suh 2007). AD divides the design world into four domains: the customer, functional, physical and the process domain.

Functional requirements (FRs) represent the main functions that a design must satisfy. In the case of the dryer for example, FRs result directly from the performance specification document (chapter 4, Table 3):

FR1: Dewater
FR2: Dry

FR3: Pelletise

FR4: No external energy

FR5: No external power

FR6: Retain calorific value

FR7: Space

FR8: No contamination

FR9: No odour

FR10: Low maintenance requirements

FR11: Robustness

FR12: Long lifespan

FR13: Low cost

FR14: No negative impact on the rest of the system

FR15: Fully- or semi-automated

FR16: Compatibility with toilet paper

Now, the design parameters (DPs) of a system are the elements of the design that allow FRs to happen. For example, if digging is a FR, then a shovel is DP of a system with which the FR can be satisfied. We cannot know whether this DP is the best one for the specific system to satisfy the FR and it is not something of importance at this point of the study. The design parameters (DPs) for the dryer are nothing more than its basic design features, as these have been previously presented in chapter 4. More precisely, the DP set consists of the:

DP1: Drums

DP2: Scrapers

DP3: Air steam

DP4: Metallic surface

DP5: Enclosure

DP6: Small size (compared to other dryers of the same principle)

In order to obtain some first, tangible insights about the system that is being examined, the FRs need to be correlated to the DPs. AD gives us this correlation, which is expressed as follows **(Eq. 1**):

$$\{FR\} = [A]\{DP\}$$

, where [A] is called design matrix of the system that maps FR vectors to DPs and is of the following form **(Eq. 2)**:

$$[A] = \begin{pmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{pmatrix}$$

The mapping process can be executed in many ways depending on what the aim is. For example, A_{nn} can receive the value X to symbolise that a specific FR is satisfied by the corresponding DP. Even equations and functions can be used if needed. More often, A_{nn} are replaced by number '1' to indicate a connection between FR_n and DP_n. Such a connection can also be written as a pair: (FR_n, DP_n) to declare the connection between the two. To start building the design matrix for the dryer, no changes will be made from what has already been presented in chapter 4. As a side note, each FR can be linked to multiple DPs and not necessarily to only one. The FRs will be arranged in the table's rows, in exactly the same sequence as they were identified during the design process (i.e. numbered from 1 to 16). The DPs will remain intact too, forming the table's columns. It needs to be highlighted that, although in linear algebra the two representations would be equivalent if the sequence was rearranged, in AD it is important to design the first design matrix by fully respecting the sequence as it derives from the designer's thought process. In a different case, the results' validity will be affected.

There are two special cases of design matrices: the diagonal matrix **(Eq. 3)** and the triangular one **(Eq. 4)**:

$$[A] = \begin{pmatrix} A_{11} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & A_{nn} \end{pmatrix} : \textbf{\textit{diagonal matrix}}, \quad [A] = \begin{pmatrix} A_{11} & 0 & 0 \\ \vdots & \ddots & 0 \\ A_{31} & \cdots & A_{nn} \end{pmatrix} : \textbf{\textit{triangular matrix}}$$

In the case that the matrix is diagonal, the design is called ***uncoupled***, whilst, if it is triangular, it is called ***decoupled***. In both these cases, the corresponding system satisfies the ***independence axiom:***

Axiom 1 (Independence Axiom): FRs need to be independent

The dryer's initial design matrix constructed by mapping each FR to its corresponding DP(s), is displayed in Table 4:

Table 4. The initial design matrix for the dryer

FRs	DP1	DP2	DP3	DP4	DP5	DP6
FR1	1	0	0	0	0	0
FR2	1	0	1	0	0	0
FR3	1	1	0	0	0	0
FR4	0	0	1	0	0	0
FR5	0	0	0	0	0	1
FR6	0	0	1	0	0	0
FR7	0	0	0	0	0	1
FR8	0	0	0	0	1	0
FR9	0	0	0	0	1	0
FR10	0	0	0	1	0	0
FR11	0	0	0	1	0	0
FR12	0	0	0	1	0	0
FR13	0	0	0	0	0	1
FR14	0	0	0	0	1	0
FR15	1	1	0	0	0	0
FR16	1	1	0	0	0	0

The first and clear conclusion that comes from the above design matrix, is that it is not diagonal nor triangular and that a diagonal form cannot be obtained, no matter how many changes are implemented. The reason is that three FRs (i.e. FR3, FR15 and FR16) are mapped with more than one DPs. Therefore, the dryer design is definitely not an uncoupled design. The question that remains to be answered is whether a triangular matrix (and thus, a decoupled design) can be acquired by transforming the matrix into an equivalent form. By reordering FRs starting from column 1 (DP1) and moving to the left in such a way so that as many 1s as possible are grouped together, Table 6 can be converted into the matrix shown below (Table 5), without loss of the generality.

Table 5. The design matrix that results from reordering FRs

FRs	DP1	DP2	DP3	DP4	DP5	DP6
FR2	1	0	1	0	0	0
FR1	**1**	0	0	0	0	0
FR3	1	**1**	0	0	0	0
FR15	1	1	0	0	0	0
FR16	1	1	0	0	0	0
FR4	0	0	**1**	0	0	0
FR6	0	0	1	0	0	0
FR10	0	0	0	**1**	0	0
FR11	0	0	0	1	0	0
FR12	0	0	0	1	0	0
FR8	0	0	0	0	**1**	0
FR9	0	0	0	0	1	0
FR14	0	0	0	0	1	0
FR7	0	0	0	0	0	**1**
FR13	0	0	0	0	0	1
FR5	0	0	0	0	0	1

The above matrix resulted from grouping all FRs that were mapped with the same DPs. Like this, table 5 might still not be a triangular one, but it shows which FRs are stopping it from becoming one. The main problem is FR2 (the drying function) which is mapped with two different DPs that are not positioned next to each other. These are DP1 (drums) and DP3 (air steam). In design terms (and non-mathematical ones), that can be translated as follows: the fact that in order for the drying function to be satisfied, both the drums and the air steam are needed, is complicating the design interdependencies within the system. Indeed, if we go back to the design phase of the problem (as described in chapter 3), the reason why both the drums and the air steam were kept as DPs, was to take advantage of both conductive (drums) and convective (air steam) drying. Consequently, this detail can now be translated into a useful insight: FR2 consists in reality of two distinct functions, FR2a (conductive) and FR2b (convective drying). This is also a first demonstration of the power that AD has as a tool to analyse a designed system. This

mathematical approach to the design challenge can lead to some very tangible, technical insights. Now, based on the aforementioned observation, Table 5 can be re-arranged as follows:

Table 6. The design matrix after breaking down FR2 into FR2a and FR2b

FRs	DP1	DP2	DP3	DP4	DP5	DP6
FR2a	1	0	0	0	0	0
FR1	1	0	0	0	0	0
FR3	1	1	0	0	0	0
FR15	1	1	0	0	0	0
FR16	1	1	0	0	0	0
FR2b	0	0	1	0	0	0
FR4	0	0	1	0	0	0
FR6	0	0	1	0	0	0
FR10	0	0	0	1	0	0
FR11	0	0	0	1	0	0
FR12	0	0	0	1	0	0
FR8	0	0	0	0	1	0
FR9	0	0	0	0	1	0
FR14	0	0	0	0	1	0
FR7	0	0	0	0	0	1
FR13	0	0	0	0	0	1
FR5	0	0	0	0	0	1

Table 6 might still not be of triangular form, but the problem caused by FR2 is solved. All FRs are connected only to 1 DP, apart from FR3, FR15 and FR16 which might be mapped to two DPs, but the latter are located in consecutive columns. For the matrix to be converted into a triangular one, there is only one last step to be made. At this point, it is much easier to recognise that if the FRs that are satisfied by the same DPs are grouped together and written down as a unified FR, then the matrix obtained will be triangular. The final design matrix that results is shown in table 7:

Table 7. The final design matrix for the dryer after grouping FRs that are satisfied by the same DPs

FRs	DP1	DP2	DP3	DP4	DP5	DP6
FR_{Group1}	**1**	0	0	0	0	0
FR_{Group2}	1	**1**	0	0	0	0
FR_{Group3}	0	0	**1**	0	0	0
FR_{Group4}	0	0	0	**1**	0	0
FR_{Group5}	0	0	0	0	**1**	0
FR_{Group6}	0	0	0	0	0	**1**

In order to obtain table 7, the FRs had to be grouped as shown below:

- FR_{Group1}: FR2a, FR1
- FR_{Group2}: FR3, FR15, FR16
- FR_{Group3}: FR2b, FR4, FR6
- FR_{Group4}: FR10, FR11, FR12
- FR_{Group5}: FR8, FR9, FR14
- FR_{Group6}: FR7, FR13, FR5

In more detail, the dewatering and the conductive drying actions are both mapped with the drums. Pelletising, automation and dealing with hygiene products require both the drums and the scrapers to be operated. This makes sense, as even the reality of the project proved that indeed they constitute challenges of higher complexity. F_{Group3} consisted of convective drying, non-usage of external source of energy and the retainment of faeces' calorific value, is mapped to the DP corresponding to the hot air steam. Maintenance, robustness and lifespan are grouped together and are linked to the metallic material. F_{Group5} consists of the lack of odour, the lack of contamination and the neutral impact of the dryer to the rest of the system. This group is mapped with the enclosure of the dryer. Finally, the limited space requirement, the low cost and the independence from external sources of power are linked to the size of the dryer.

The re-arranged design matrix of the dryer that is depicted in table 8, can now be written in its mathematical form:

$$[A] = \begin{matrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{matrix} \quad \textbf{(Eq. 9)}$$

As it can be deducted from Eq. 9, the final dryer design matrix is a ***triangular*** matrix. Therefore, according to theory, and since the order of DPs has not changed, the dryer design can be converted into a ***decoupled design***, satisfying AD's **independence axiom**.

What the satisfaction of the independence axiom is telling us is that the dryer design (or better, the intended design corresponding to matrix 6-1) has the potential to be an acceptable solution. The fact that there is only one element (A_{21}) that does not allow the matrix to be diagonal is showing that the expected robustness of the system is also potentially high. If someone wished to improve the design, they would have to remove all dependences between conflicting FRs. In other words, between FRs that are satisfied by the same design elements. Similarly, FRs that rely on more than on DPs, for example the ones represented by FR_{Group2}, should be broken down into sub-functions that are independent with each other (exactly in the same way that FR2 was broken down into FR2a and FR2b). This independency leads to higher probability for each FR to be satisfied since it only relies on one DP.

This last remark is echoed by the next axiom of AD, the ***information axiom:***

Axiom 2 (Information Axiom): Keep the information content of a design to its minimum

The information content I_i for a given FR_i is defined in terms of the probability P_i of satisfying FR_i **(Eq. 6)**:

$$I_i = -log_2 P_i = -log_2 \int_{dr^1}^{dr^u} p_s(FR_i) d(FR_i)$$

In the general case of m FRs, the information content for the entire system Isys is given by **(Eq. 7)**:

$$I = \sum_{i=1}^{n} I_i = \sum_{i=1}^{n} -log_2 P_i$$

What the information axiom states is that the design with the smallest *I* is the 'best' design, since it requires the least amount of information to achieve the goals set by the scope. In order to implement the above equations in the case of the dryer, a slight modification is needed. If the information axiom is applied as defined by AD, the final result will not be a fair reflection of the dryer's capabilities. Some FR groups are more important to the dryer's performance than others and assigning a probability (no matter how big or small) alone would not result into a fair result. A weight needs to be assigned to each group of FRs, according to their importance. For instance, the groups related to drying and dewatering functions are crucial to the design's success and their weight needs to be respectively higher compared to other groups of FR. That would also allow certain DPs that do not affect the system's *I* indicator to be improved in the future. In the case of the dryer we could assign the following weights (a_i) and probabilities (P_i):

$P_{FRGroup1}$=0.8, a_1=1.26

$P_{FRGroup2}$=0.6, a_2=1.15

$P_{FRGroup3}$=0.7, a_3=1.31

$P_{FRGroup4}$=0.85, a_4=0.76

$P_{FRGroup5}$=0.4, a_5=0.76

$P_{FRGroup6}$=0.5, a_6=0.76

Using equation 2-7, the above probabilities and weights give I_{SYS}=3.86. I_{SYS} represents the amount of information needed to satisfy the FRs. In order to understand what this number means, all Is are benchmarked against 0, which is the minimum amount of information needed when all probabilities are equal to 1. On the contrary, in the unfavourable scenario of having zero probabilities, then the information required is infinite. Although there is not another design to compare the dryer's performance in this field, 3.86 seems to represent a relatively achievable set of FRs, but in the meantime it comprises a fair reflection of the complexities that are involved in the challenge.

Another conclusion regarding the dryer design's complexity can derive from the initial design matrix (Table 5). The amount of modifications (FR re-orderings) required to reach a decoupled design (Eq. 9) reveals that the complexity during the design challenge was

primarily an imaginary ***complexity***, in other words it was because of the designer's (i.e. the author's) limited knowledge and background of drying technologies when the project began.

This concludes the analysis of the dryer's resulted design using AD. The design can be considered as validated from AD's perspective as it satisfies the independence axiom (constituting a decoupled design) and it is not too far away from the optimal information number (3.86 versus 0).

5.3 Using C-K theory to evaluate the dryer design in terms of innovation

The dryer's scientific testing along with the application of AD lead to the conclusion that the dryer's concept has high potential to be successful in meeting the FRs set, and therefore, it can be considered as proven. What has not yet been assessed is the design techniques that led to the final design and how these techniques are linked to the research question of this study. To attempt answering this question, another theoretical tool is needed: one that can address the conceptual evolution of the dryer until its final version presented in this study. For this purpose, the C-K theory will be utilised.

A review of the dryer's development process using C-K theory includes the study of all significant steps in this design journey and their exact sequence in the process. Everything started from the initial (yet inexistent) concept C_0 which refers to a "*device to dry the sludge that comes out from the screw and to convert it into combustible matter*" (see initial scope as described in chapter 3, section 3.4.1). Immediately a process of breaking down C_0 into multiple alternatives and potential sub-concepts began. Then, these sub-concepts were explored, some of them tested and rejected and some others were further explored and finally accepted. During the whole process, a constant interaction between the knowledge and the concept space was taking place. This research (design and development) journey had multiple levels before reaching the current version. The movement between the two spaces can be described by four primary operators: C→C, C→K (conjunction operator), K→C (disjunction operator) and K→K. (Le Masson et al. 2017). The K→K corresponds to the exploration of knowledge, in other words to the process of delving into a certain knowledge space. If the knowledge is new (acquired),

then the phenomenon of ‘expansion of the knowledge space’ takes place. In the case of the dryer, extensive research (expansion of the knowledge space) was noticed in particular in the fields of drying technology and sludge treatment. The K→C (disjunction) operator refers to the creation of an undecidable proposition based on a decidable proposition in K. In the dryer case study, the disjunction operator was happening in every level of decision-making and problem-solving. It has to be noted that the K→C operator does not only concern the cases when new knowledge is required. Even if the knowledge already exists, there is still a continuous mapping between the designer’s knowledge space and the concepts they create or examine. Conversely, the C→K operator describes the creation of a decidable proposition based upon an undecidable proposition in C. In other words, it only happens once, when (and if) a novel concept is created and gets validated. Then it moves to the knowledge space and becomes part of the knowledge acquired during the process.

The following few lines summarise C-K. Every design process starts with a brief which leads to the first concept created in the C-space, symbolised as C_0. The C-space is constantly informed by the content in the K-space. Various sub-concepts are then explored and developed until a final concept which is not contained in the K-space is generated (hence the term ‘generativity’). If the concept is proven (through validation and testing), then it moves to the K-space and can be considered from that point onwards as established knowledge. Figure 31 represents a high-level visualisation of the dryer’s journey:

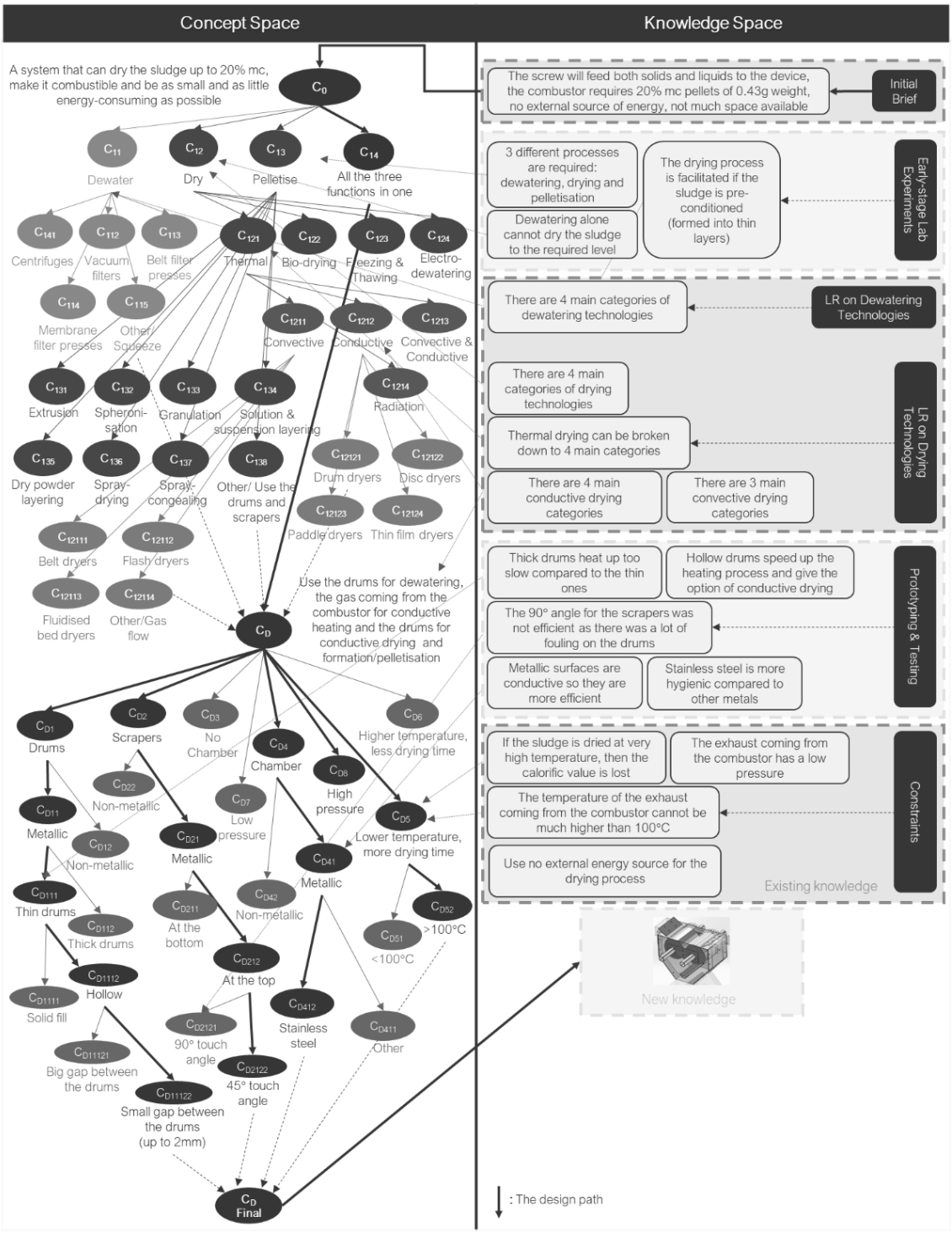

Figure 31. The C-K model representation for the dryer

The model described above might be decent to explain the design process of the dryer from a logical and cognitive perspective, but there is still something missing to connect the logic of the dryer's design process to specific, tangible and measurable techniques. To achieve this goal, a model that relies on C-K, but which leads to more quantitative

results is needed. That model is the C-K/Ma (Ma stands for matroidal) model which is explained in detail in chapter 2 (paragraph 2.4.2). When designing a new technology (or technical system) there are basically three design techniques to use:

1. Deletion/Contraction: Design a product by relying solely on already existing techniques.

2. Extension: Develop a new technique which aims at the development of a new product.

3. Co-extension: Design a new technique, aiming at re-ordering all the interdependencies between the other techniques.

The application of the C-K/Ma to any newly-designed technology is not a simple matter. It would be a huge waste of time and effort to analyse (in terms of design techniques) every single concept or element designed throughout the process. This is why focusing on the important features alone is crucial. In the case of the dryer, the important elements are almost the same as the ones described in axiomatic design as design parameters (DPs). The dryer was then broken down into its main functions, namely convection, conduction and dewatering. Using the most common technologies in the market as a reference, each function was represented as a closed ('working') system consisted of three basic elements. Following this rationale, it was found that the dryer was the result of **one coextension** and **a couple of extensions**. Therefore, its development follows the trend of the majority of patents, which entail at least one coextension and several extensions. Figure 32 illustrates the design techniques for the dryer's case.

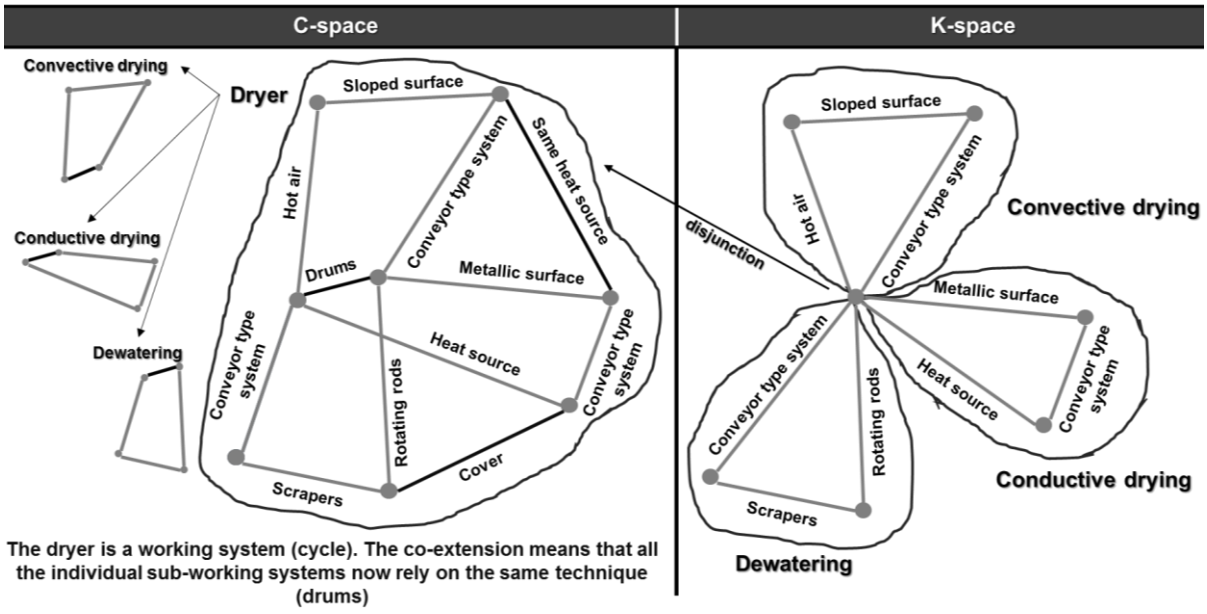

Figure 32. The C-K/Ma model for the dryer

The three elementary functions, which can be independent, are located in the K-space, whilst the concept of the dryer is developed in the C-space, in a way that an overall working system is created. As shown in Figure 34, the addition of the drums expands the number of edges of all the three individual functions (dewatering – convective drying – conductive drying), which indicates that the drums are necessary for all the subsystems to operate.

The dryer confirmed the hypothesis that derived from (Strumsky and Lobo 2015) research claiming that almost all patentable technologies belong to an extension-driven regime, but they can only emerge when at least one coextension appears. Even the numbers provided by the authors coincide with the dryer's case. Their research revealed that for x number of coextensions, x^n extensions are enabled, where $1 \leq n \leq 2$. Indeed, in the case of the dryer there is only 1 coextension (x=1), and 2 main extensions around it: for any $1 \leq n \leq 2$, x^n gives us 1.

5.4 Key findings from chapter 6

The dryer case study was analysed using design theory, and more precisely axiomatic design and C-K theory. The application of AD theory showed that the dryer design satisfies one of the two main axioms of AD: the *independence axiom*, which can work as an indicator that the design has potential to satisfy the FRs set by the specification

document and to be robust enough. The findings complemented the data-driven validation that occurred in chapter 5, with a validation from a design theory perspective this time. Concerning the second AD axiom (*the information axiom*) there is not another design for the dryer to be compared with to get conclusive results. However, the system's information indicator (I_{SYS}) is not much higher than the one corresponding to the ideal scenario (equal to zero). Therefore, the designed system looks promising in terms of complexity as well. It was further shown that any complexity remaining in the system was due to *imaginary complexity*, meaning complexity that is related to the designer's initial unfamiliarity with drying technologies, rather than real complexity caused by the

In terms of improvements, AD analysis indicates that if the FRs consisting $FR_{Group1} - FR_{Group6}$ became independent so that each one relies on a different DP, the system would increase its chances of robustness due to a decrease in the probability of failure. This finding though, could be argued, as it contradicts the basic approach followed throughout the process: the holistic approach. The holistic approach on one hand would be weakened if such a finding had to be implemented, but on the other hand it is thanks to it that the complexity of the designed system was kept to low levels. Therefore, the probabilistic approach regarding reliability, contradicts the designerly approach of 'whole system design'. And this can be considered as one of the collateral findings of the present study.

This is -arguably- the first case that the C-K/Ma model is applied to gather insights from an ongoing real-world project. One of the reasons is because it requires significant amount of time and effort to identify the right elements, and also the right scale to analyse. An interesting proposition coming from the study is that the C-K/Ma model could be used as a metrics to measure the innovativeness of a new design and the impact that it might have on other designs.

5.5 Summary and answer to the research question

The key finding that resulted from the analysis is that the dryer's design process involved one coextension and two extensions, confirming the hypothesis formulated by other recent studies on U.S. patents (Strumsky and Lobo 2015) that **patentable technologies require at least one coextension to be present**. This leads to an answer to the research question of the present study:

The design technique called 'coextension' was identified as the key technique leading to the invention of the dryer

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The answer to the research question will be further discussed and triangulated to recall evidence from the literature, the case study analysed, and an experiment designed to validate the findings.

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6 DISCUSSION

Objective 5: discuss the research findings.

This chapter brings together and discusses the key findings from the overall research. It recalls evidence from design theory (literature), the case study and experiment developed to provide support for the hypothesis that *Coextension was the core design technique that led to the invention of the dryer and appears during the generation of innovative concepts*. Also, the knowledge points derived from the overall PhD journey are discussed.

Keywords for this chapter: *discussion, contribution to knowledge, key learnings, PhD journey*

6.1 Research Limitations

The limitations of the study can be divided into two categories: subjective and task-related ones. The subjective limitations are related to lack of expertise or experience of the researcher when facing a specific challenge, whilst task-related limitations derive from the difficulties surround certain tasks.

The first task-related limitations faced early on in the research concern the ambiguity of certain notions in design theory, as well as the lack of easy access to eye-opening information. Such implications were faced when attempting to retrieve basic information about design theory and also, when reviewing literature of other design research topics. These limitations were overcome by dedicating time and effort on ensuring that the research findings are valid and aligned with formal theories of design rather than on just random journal papers. This is echoed by the fact that even design journals (mainly Design Studies, Design Science, Design Issues, Res Eng Des and She Ji) often see the same design phenomena from different perspectives and use different approaches or terminologies. This process was also supported by interacting with experts in the field who provided advice and material to put the research back on track whenever needed. As a generic piece of advice, the sooner the theoretical framework of a study is defined, the easier the research journey will be.

Other practical implications met in the course of this PhD journey are related to constraints, and mainly time. These were task-related limitations, as the topic included

several knowledge domains (design theory, engineering design, drying technology and cognitive science). Thus, the right decisions had to be made in order to avoid dedicating time to the wrong tasks, which would risk disrupting the PhD track. Such an example is the dryer testing which, despite the fact that the simplest approaches were always followed, lasted for much longer than initially planned. At some point, this risked the on-time completion of the PhD and some other tasks had to be expedited to make amends.

Regarding the case study, the main implications to be discussed are related to the challenges faced for someone that does not come from a relevant scientific background. **The result of this design challenge can be generally characterised as successful, since the concept was proven, the research team considers the dryer to be part of the solution and a patent No. 741662 was thus submitted** (Appendix A).

It is an irony of this study that one of its biggest advantages, that is the generous funding, the diverse background of the researchers surrounding it and the interesting challenge were also its limitations. Different backgrounds, except for providing a more holistic approach to a problem when they get integrated, they can also cause a conflict of approaches or opinions when it comes to decision making. In the case of the dryer, this limitation caused delays in multiple occasions. These situations were always faced by sympathy to opposing opinions, open-mind, but also decisiveness to proceed with the option that seemed the most appropriate when time was running out.

Apart from limitations in terms of expertise or experience, there were also certain technical limitations linked to the dryer case study. These limitations were mainly due to the lack of resources, and more precisely time budget and equipment, that are required to build an 'ideal' testing rig for the dryer. The biggest challenges faced were related to the lack of budget and time to purchase an automated mass flow rate-regulating equipment. This barrier was overcome by building a simplest rig which was able to measure and regulate volumetric air flow rate. This way, the mass flow rate which results from multiplying the volumetric air flow rate by the air's density. This relies, in reality, on the same principle as integrated mass flow rate regulators.

The above example is characteristic of the mentality in which all technical obstacles were approached. The design principle of **simplicity** was implemented whenever and however possible during the whole process. Despite the limitations of this approach, there were

occasions where the result was obtained faster than it would have been if a stricter scientific approach was followed, while the result was still within the range of acceptable results.

6.2 Key findings in the field of design theory

The findings that resulted from applying design theory on the dryer case, as presented in chapter 5, suggest that the design technique of coextension constitutes the answer to the study's research question. This finding is already supported by the literature (Strumsky and Lobo 2015), which indicate that coextension is an ever-present technique in US patents. More precisely, coextension is the technique that constitutes the added element (the drums in the case of the dryer), as necessary for the pre-existing working systems to operate. Hence, thanks to coextension, extensions are facilitated and the genericity (meaning the applicability) of the novel design expands.

In order to go one step further and these results, the first ever 'generativity test' (Appendix B) was created. The test is 1) able to identify the aforementioned design techniques and 2) able to correlate them with the most commonly acknowledged cognitive skills: fluency (how many correct solutions), flexibility (how many distinct solutions) and originality (how many unique solutions).

The test (to-date) has been tried on 50 people of various ages (a range from 15 to 60 years old) and of different sexes. The results are showing that younger people tend to perform better and there is no significant correlation between performance and person's sex. What is of real interest, is that there is a high correlation between originality score and coextension score. The full results will be presented in the context of a journal paper that is being drafted. Indicatively, it can be safely concluded by current results that about 20% of the participants are able to demonstrate the skill of coextension, whilst more than 60% possess the skill to apply the design technique of extension.

These results are aligned with the hypothesis that coextension is a far rarer technique, while extension constitutes the most common technique of building upon pre-existing designs. The triangulation of evidence recalled from the case study, literature and the experiment under development provides adequate support to the hypothesis that coextension is the design technique which is crucial and ever-present in the invention

process.

6.3 Future Work

There are two basic dimensions to which future work must be directed. The first one is related to the dryer and the second one to the generativity test. The dryer's next version is already being designed and some of the modifications are currently being implemented. The dryer's efficiency has to be increased by improving insulation, fully enclosing the system and converting the dryer from a convection-based dryer to a conduction-based dryer. The dryer's concept will also be converted into a modular one, as a further drying and another pelletising layers will be added to the system, without altering the existing dryer concept.

That does not mean of course, that improvements (according to findings from chapters 3 and 4) there is room for improvement. The most important changes are as follows: 1) the dryer will be enhanced with two processing layers: one for post-drying and another for further pelletisation. This system, named 'modular dryer system' will look like three subsystems being attached together (as in Figure 34). 2) the main drying force of the first layer of the dryer will no longer be mainly convective, but mainly conductive. The tube that transfers the exhaust air from the combustor will be feeding the dryer with hot steam passing through the sealed drums. The heated air will then be circulated inside the drying chamber to remove moisture particles and provide convective drying to the flocs (Figure 35). Moreover, fins will be added inside the drums, as based on calculations, this is believed to enhance the drums' heat rate coefficient.

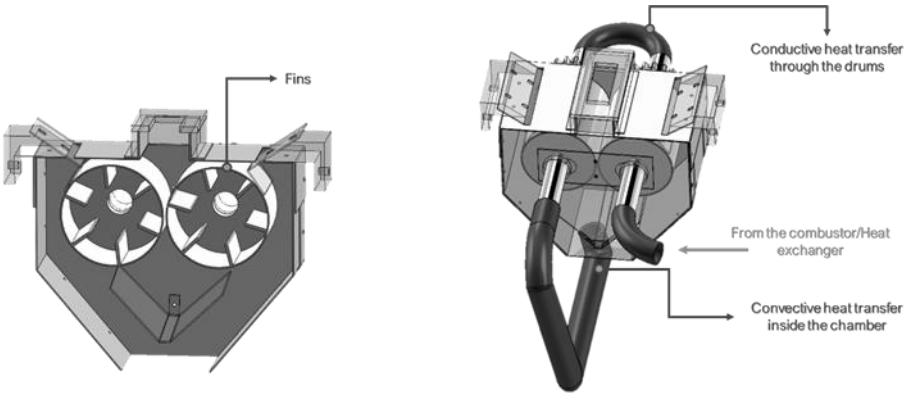

Figure 33. A draft drawing of some of the changes needed to be realised

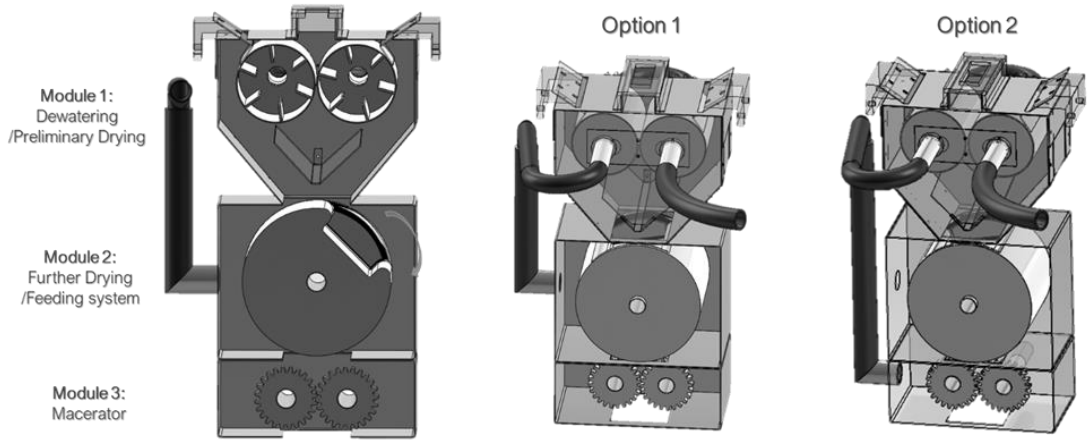

Figure 34. A draft depiction of the 'modular concept' for the dryer

The generativity test, on the other hand, will provide further evidence to support the answer to the research question and to link (for the first time) the design techniques with easily-tested cognitive skills. If for example the research hypothesis that *coextension is correlated with originality*, then it won't be necessary to test coextension as a separate skill. However, the knowledge that these two skills are correlated will contribute immensely to cognitive science and employers will know that by testing originality, they are also testing a skill that is highly-related to invention. If the hypothesis does not get confirmed, then the value of the generativity test will be even higher, as it will be the only one (or the first one if another appears) to test the specific skill, as well as all other design skills.

References (chapter 6)

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7 CONCLUSION

The study was motivated by the author's interest in design-driven innovation and the challenging case of the 'reinvent the toilet' project. It was also motivated by the gap in knowledge relating to the exact design techniques that drive invention. Its aim was to better understand the way that invention occurs in design (and science). For this study to end, a real-world invention had to be developed and several theoretical implications had to be overcome.

In the beginning, the case study (dryer) was assigned as a real-world problem that had to be solved in the context of the 'reinvent the toilet' project funded by the Bill & Melinda Gates Foundation. In parallel with the research and development activities that concerned the technology that was later designed and patented, there was an ongoing research for an appropriate theoretical framework to fit the activities in. Since the scope of the challenge was partly science- and partly design-related and the teams involved were coming from both disciplines, there was a thought to attempt and bridge design and science. Moreover, as the challenge was considered as a complex one, there was a keen interest in exploring how designers solve such problems. Hence, very soon, the focus was put on problem solving (in design and in science) and more specifically on complex problem solving. When the study was enriched with further findings indicating that design is not about problem solving (although it does include it in its overall process), the problem was approached from a different perspective, aligned with formal design theory.

The dissertation is hoped to contribute new knowledge in the following directions: 1) disseminate modern theory as practical tool for design researchers, 2) provide the first generativity test constituting innovation measurable for the first time and correlate it with other cognitive skills known. The findings from this study could be of great benefit to design theorists and theorists of innovation. In answer to the question "*how are innovative concepts generated in design and science?*", the evidence from the case study, the literature and the first results from the generativity test strongly suggest that 'the design technique of coextension' might be the right answer, but it is not yet conclusive.
The unique contributions to knowledge as they derived from this study are listed below:

Major

- **The dryer** proof-of-concept prototype (patent No. 7416662 – Appendix C)
- The **design methodology** followed (Figure 14, page 48) which led to a successful design

Minor

- **The generativity test** developed, which constitutes the first test ever created to capture the design techniques of extension and coextension.

The design methodology followed during the design and development process of the dryer is representative of the way that designers think and approach problems, either within or outside of the scientific scope and seems to be promising as it led to a successful design. Hence it could be used in similar contexts, where both design and scientific challenges need to be addressed.

There are likely to be problems where a sub-optimal solution, regardless of how it derives or whether it is complete or not, is better than no solution at all. In this study, there is enough evidence that in design thinking, which root back in the oldest, simplest and most intuitive ways of solving problems, but which could be proven useful to encounter modern, complex problems. After all, the categorisation into disciplines and problem types is nothing more than a human invention, enabling us to specialise and face each problem more efficiently. Ultimately, the world that surrounds us is one and its problems are there, waiting to be faced, indifferently of existing specialisations and knowledge domains.

APPENDICES

APPENDIX A – Common design methods

Title	Description	Purpose	Design Stage
Abstraction	Represent a concrete problem into a more abstract one	To expand the solution space, seeking for more alternatives	S_0
Adaptation	Modify or partially transform an existing process or system in order to meet different conditions	To obtain a reliable solution for new conditions or environment	$S_1 – S_2$
Aggregation	Combine existing subsystems into a single system, or combine functions into one	To achieve a simplified structure with enhanced properties	$S_1 – S_2$
Alexander's component method	Identify contributing components to a complex design problem	To create a suitable sequence of design considerations and decisions	$S_0 – S_1$
Analyse-Theorise-Delineate-Modify	Recommend a problem-solving sequence with forced iteration	To formulate a theory of design	$S_0 – S_1$
Analysis of Interconnected Decision Areas (AIDA)	Identify components of a problem and their relationships	To group components of the problem to reduce impact of interrelations	S_0
Analysis of Properties (Attribute Listing)	Analyse every property, list all attributes of the thing to be designed and consider each one to decide whether changes are needed or not	To improve an existing design	$S_0 – S_1$

Analysis of Variance (ANOVA)	Mathematical statistical treatment of experimental data to discover influences of environment properties on the behaviour of a system	To identify those properties that have the greatest effect on behaviour	$S_0 - S_1$
Art Gallery Method	Display several concepts or layouts with alternative solution proposals, discuss advantages and disadvantages of competing layouts by assessing them in a team situation	To select and synthesise the most favourable constructional structure from several proposals	$S_0 - S_1$
Axiomatic Design	Use simple axiomatic statements to guide selection among proposed alternative solutions	To apply linear algebra to design decision making	$S_1 - S_2$
Benchmarking	Compare a design of interest with another (usually an established one, e.g. belonging to a competitor)	To assess a (usually new) design based on existing standards	$S_2 - S_3$
Black box	Define/Present the inputs and outputs of a process, without digging into details of how the transformation is done	To observe and modify the transformation in isolation, independent of the mechanisms that cause the transformation	$S_0 - S_1 - S_2$
Blockbusting	Overcome mental blocks and prejudices by freeing the mind	To avoid the phenomenon of 'design fixation'	$S_0 - S_1$
Boundary Element Method	Approximate iterative computer solution of systems of equations with assumed boundary conditions, by dividing a continuous	To find a close analogy to the behaviour of a physical phenomenon	$S_1 - S_2$

	geometric boundary into discrete elements, to model physical phenomena		
Boundary search/shifting	Investigate effects of redefining the boundaries of the system	To distribute tasks among systems and operators better	$S_0 - S_1$
Brainstorming	Collect ideas in free discussion without criticism	To find many solutions to a given problem	S_1
Brainwriting	A number of participants, write down 3 ideas each, within 5 min, then pass on to next person to think of 3 similar ideas	To come up with conceptual solutions	S_1
Breakthrough thinking	Generative innovative ideas and products by implementing certain guidelines for breakthrough thinking	To generate an innovative solution	S_1
Cause and effects analysis	Analyse consequences ("effects") attributed to causes (causally or statistically)	To understand relationships between features and phenomena	S_0
Check lists	Use suitable lists of items as guideline for considerations	To check the completeness of task	$S_0 - S_1 - S_2 - S_3$
C-K Theory (incl. C-K/Ma model)	Retrospectively reflect on the generation of a conceptual design	To depict the idea and knowledge generation process and assess a novel design's impact	$S_1 - S_2$
Computer-aided design/drafting (CAD), computer-aided engineering (CAE), and computer-aided manufacture (CAD/CAM)	Using a computer to perform Computer-Aided Design (CAD), conduct suitable analyses to assist designing (CAE), and convert data about constructional parts for	To capture the concept of a design (geometry, tolerancing, all considerations toward design properties) for	$S_1 - S_2 - S_3$

	CAD/CAM	retrieval and modification	
Computer Integrated Manufacturing (CIM)	Computer control of manufacturing plant and inventory	To supervise the manufacturing process	$S_1 - S_2 - S_3$
Concept map	Show a set of concepts, and by labelled links describe their relationships, as a hierarchical or network representation	To improve understanding of a situation by visualising concepts	S_0
Concept Selection	Pair-wise comparisons of proposed solutions according to selected criteria, performed in teams	To select an optimal solution among given proposals, and improve it	$S_0 - S_1$
Concurrent engineering	Perform design work on the product and the manufacturing process at the same time	To achieve a trade-off between design features and manufacturing cost/difficulty	$S_2 - S_3$
Continuous improvement	Constantly look for ways to improve the operation of a process or an organisation	To achieve incremental changes, one at a time, minimising the risk of unacceptance or failure	$S_0 - S_1 - S_2 - S_3$
Cost-Benefit Analysis	By analysing costs and benefits in monetary terms, select a solution among the proposals	To identify a financially optimal solution	$S_0 - S_1 - S_2$
Cost calculation	Calculate costs of components/products based on either actual or empirical data	To estimate the potential cost of a design	S_3
Critical Path	Graphically represent the	To facilitate project	$S_1 - S_2 - S_3$

Network/Planning/Method	envisaged activities and their duration	management by identifying risks and minimising them	
Decision Tree	Keep records of decisions as a hierarchical tree	To allow retracing of decision steps	$S_0 - S_1 - S_2 - S_3$
Delphi Method	Gather experts' opinions on a novel design	To predict and avoid any potential problems that might be encountered in the future regarding the design	$S_2 - S_3$
Design catalogue	Collected and categorised information about possible solution principles to fulfil a function	To present information to assist creative search for modes of action	$S_1 - S_2$
Design for properties and life cycle	Collect information about favourable principles, forms, and arrangements that will optimise the system to be designed for each property (cost, functional integration or separation, assembly and disassembly, testing, maintenance, reliability, safety, serviceability, ergonomics, environment etc.)	To make knowledge available to and directly usable for designers	$S_2 - S_3$
Design Structure Matrix	Generate and process a matrix of precedence relationships among anticipated steps and variables in designing a particular system	To reduce the needed number of iterations in a decision and optimisation process	$S_1 - S_2$
Experimentation	Obtain desired statistical values and trends through testing and data gathering	To determine the level of acceptance of a prototype	$S_1 - S_2$

Failure analysis	Observe and diagnose failures to establish causes and progresses	To obtain information for future designs	$S_1 - S_2$
Failure Mode, Effects, and Criticality Analysis (FMECA)	Analyse possible failure modes in a proposed system, establish possible consequences ("effects") from each failure (as a network of interactions), estimate statistical probability of occurrence	To estimate reliability, durability, dependability of a proposed system, find ways of improving them	$S_2 - S_3$
Fault Tree Analysis (FTA)	Analyse possible failure modes in a proposed system, establish possible consequences from each failure (as a hierarchical tree structure of interactions), estimate statistical probability of occurrence	To estimate reliability, durability, dependability of a proposed system and find ways of improving them	$S_2 - S_3$
Fishbone diagram	Diagram main influences and causes on the behaviour of a system	To clarify sub-problems arising in solving a design problem	$S_0 - S_1 - S_2$
Focus Group Interview	Conduct interviews with potential customers as targets for a product	To identify customer requirements	$S_0 - S_1$
Function costing	Perform regression analysis of the acquisition costs on a size range of a purchasable constructional parts	To predict potential cost of a proposed system	$S_2 - S_3$
Function decomposition	Divide a more complex function into smaller and simpler functions	To enable the identification of easier solutions by redefining and concretising functions	$S_1 - S_2 - S_3$

Fundamental Design Method	Use guidelines for goals to start a design process	To enhance creativity	$S_0 - S_1$
Gantt chart	Show the time taken (planned or estimated) for a set of activities	To plan activities and track progress	$S_0 - S_1 - S_2 - S_3$
Granta—Cambridge Engineering Selector (CES)	Select materials of construction and form (shape) from considerations of several material properties, and manufacturing processes	To optimise materials specification and usage	$S_2 - S_3$
Ideals concept	Generate an ideal solution and degrade it to be make it realisable	To improve over existing systems by a leap	$S_1 - S_2$
Incubation	After thorough preparation of the problem, take a break to allow the subconscious to work	To think of possible solutions by intuition	S_0
Interaction net/matrix	Find interactions and relationships among features and variables for a system	To obtain an efficient sequence of establishing properties	S_0
Iteration	Starting from assumed values, obtain progressively closer approximation of values	To identify solution(s) for a system with complicated interactions	$S_0 - S_1$
Life cycle Engineering	Take all phases of the life cycle into consideration, by formalised procedures	To minimise life cycle costs and influences on the environment	$S_1 - S_2 - S_3$
Market Research	Systematically collect and classify market information	To establish marketing conditions	$S_0 - S_1$
Mind map	Map various concepts and their relationship to a central concept	To improve understanding of a related set of concepts	$S_0 - S_1$
Morphological	Enumerate possible	To obtain many	S_1

matrix/scheme	procedures to solve partial functions, in a matrix form	solutions by combinations of function carriers and variation in their arrangement	
Objectives tree	Generate a list of objectives and sub-objectives (requirements and their priorities), diagrammed in the form of a hierarchical tree	To obtain a prioritised design specification, show relationships among requirements	$S_0 - S_1$
Optimisation	Find an optimal solution to a problem, use mathematical techniques to find an optimal set of values according to a single criterion, or multiple criteria	To select and improve solution proposals	$S_1 - S_2 - S_3$
Pareto distribution/diagram	Arrange observations according to magnitude from largest to smallest, give careful consideration to the largest	To identify the most important issues	S_0
Pugh method	Concept selection method	To select an optimal solution among given proposals, and improve it	S_1
Quality function deployment (QFD)	Develop a set of charts according to recommendations to relate two viewpoints about a proposed product, a "house of quality"	To capture the "voice of the customer" and making it heard throughout the product realisation process	$S_2 - S_3$
Rapid prototyping	Produce a tangible model of a constructional part or subassembly in a plastic (or metal) material under	To obtain a solid model that can be handled, assess its suitability	$S_1 - S_2$

	computer control, from a computer representation (solid modelling)		
Reverse engineering	Disassemble a realised product or design (usually from a competitor) to generate a set of manufacturing documentation (detail and assembly drawings)	To copy a design or modify it in minor details	$S_1 - S_2$
Six coloured hats	Use the concept of hats to signify (show or encourage) different modes of thinking	To separate/encourage all thinking modes	S_0
Strengths–Weaknesses–Opportunities–Threats (SWOT) Analysis	Analysis of a situation, by verbal analysis and quantitative evaluation	To formulate a vision and mission statement for an organisation or a product	S_0
Structured Analysis and Design Technique (SADT)	Obtain flow chart of process to be investigated or to be designed, with chronological chart of alterations to keep track of developments, using interviews to gather information (facts, problem identification, opinions on solutions, etc.)	To define transformation process, record progress of the design process	S_0
Storyboarding	List each item to be considered on a separate template (or sticky note) and rearrange plausible sequences	To identify alternative sequences of items	$S_0 - S_1$
Taguchi Experimentation	Identify the main influences that can disturb an operational or manufacturing process by performing a set of controlled statistical tests	To identify robust solutions that withstand the disturbances	S_3

Taguchi philosophy	Reduce variation (variance, standard deviation) in properties, aim to achieve a consistent variation (statistical variance, standard deviation) of values around an optimal mean	To make the product 'immune' to variations in external and manufacturing conditions	S_3
Tolerance analysis	Computer-aided analysis of tolerance accumulation and six-sigma limit determination	To identify influences of tolerance contributions	$S_2 - S_3$
Total Quality Management (TQM)	Continuous improvement of products' quality by applying techniques of quality control	To create an environment where employees continuously improve their ability	S_3
Trend studies	Study (time) trend of certain product/design variables	To predict or estimate near-future development of a concept or product	S_3
TRIZ	Computer-aided invention search method	To present object information as analysed from numerous patents and suggest a procedure of invention that can be applied to design work	S_3
Value Analysis/ Engineering	Analyse and criticise an existed or proposed solution	To reconsider and improve certain properties of a design	$S_0 - S_1$
Weighted rating	Select criteria, assess weights for each criterion, evaluate goodness of each solution proposal with respect to each criterion, multiply weight	To compare each solution to a non-specified ideal one	$S_1 - S_2 - S_3$

	times goodness, add to obtain an overall rating or a percentage rating		

APPENDIX B – Literature Review Results

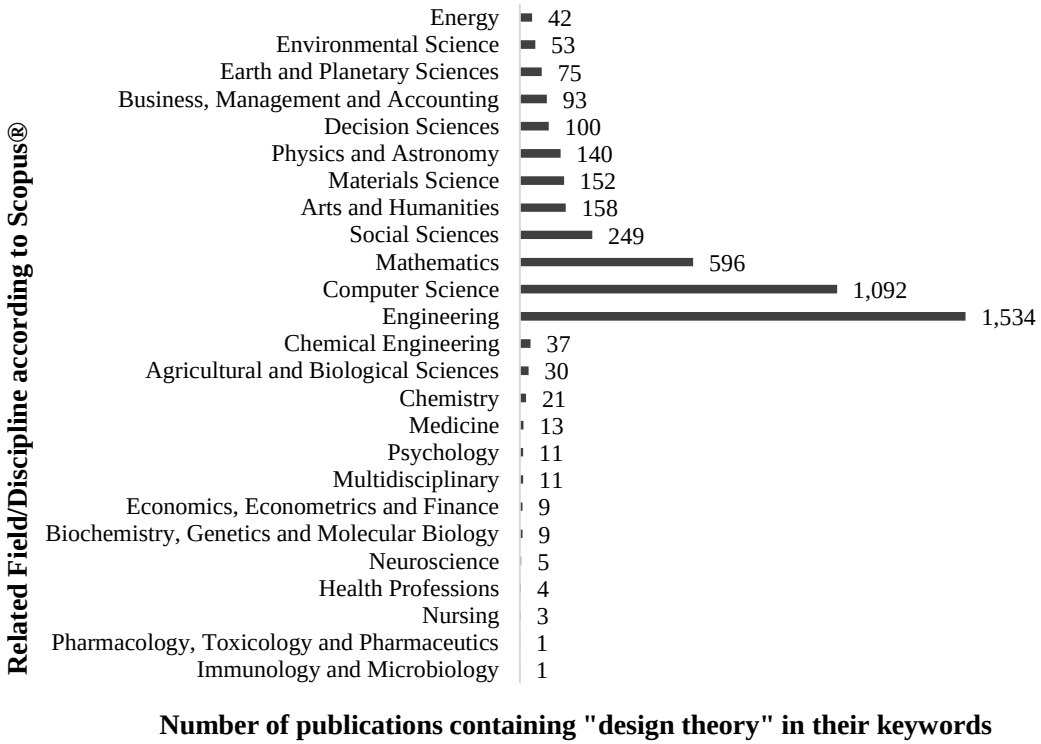


Figure B-1. Publications containing the term **"design theory"** in their list of **keywords**, according to Scopus® database, as to 17/10/2018.

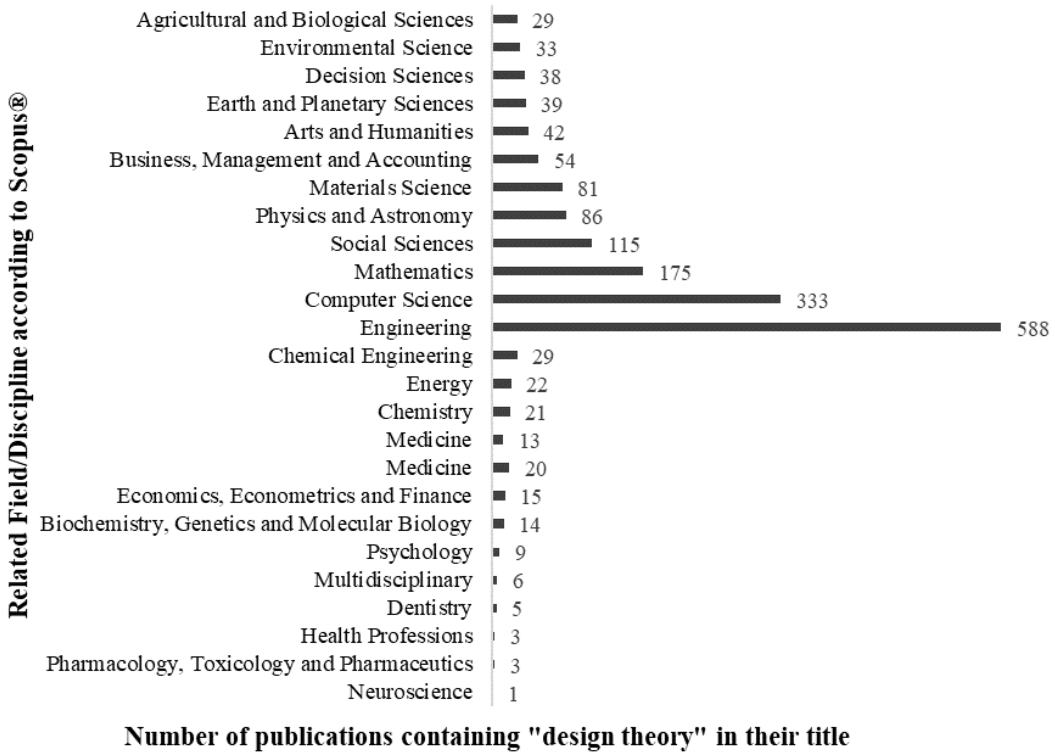


Figure B-2. Publications containing the term **"design theory"** in their **title**, according to Scopus® database, as of 17/10/2018.

Table B-1. The results of the systematic literature review, as of 25/10/2018.

Authors & Year	Title	Source title	Cited by
(Hatchuel et al. 2018)	Design theory: a foundation of a new paradigm for design science and engineering	Research in Engineering Design	4
(Le Masson et al. 2016)	Design theory at Bauhaus: teaching "splitting" knowledge	Research in Engineering Design	8
(Le Masson et al. 2013)	Design theory: History, state of the art and advancements	Research in Engineering Design	19
(Le Masson and Weil 2013)	Design theories as languages of the unknown: Insights from the German roots of systematic design (1840-1960)	Research in Engineering Design	18
(Hatchuel et al. 2013)	Towards an ontology of design:	Research in	23

	Lessons from C-K design theory and Forcing	Engineering Design	
(Frey et al. 2009)	The Pugh Controlled Convergence method: Model-based evaluation and implications for design theory	Research in Engineering Design	49
(Hatchuel and Weil 2009)	C-K design theory: An advanced formulation	Research in Engineering Design	226
(Reich 1995)	A critical review of General Design Theory	Research in Engineering Design	67
(Tomiyama 1994)	From general design theory to knowledge-intensive engineering	Artificial Intelligence for Engineering, Design, Analysis and Manufacturing	41

APPENDIX C – Patent No. 7416662

The following figure (Fig. 1 – 8) are part of patent No. 7416662 submitted as a result of Cranfield University's research teams in the context of the BMGates Foundation project. The dryer corresponds to Figure 6.

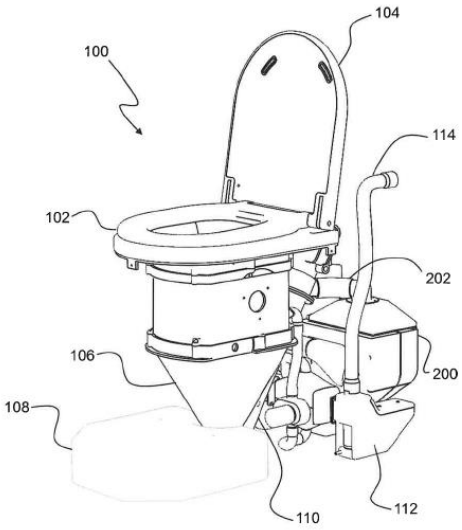


Fig. 1

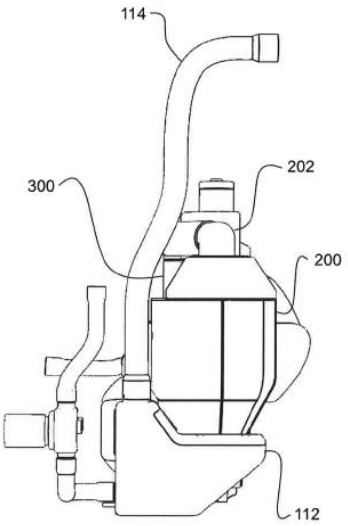


Fig. 2

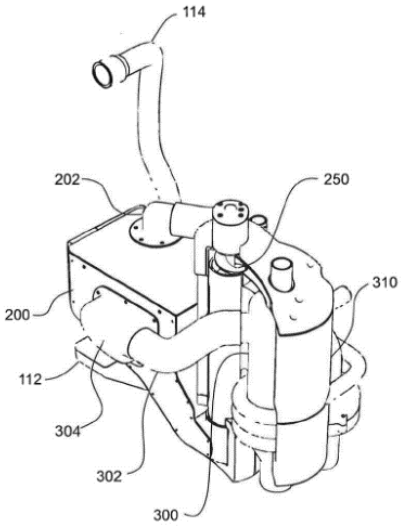


Fig. 3

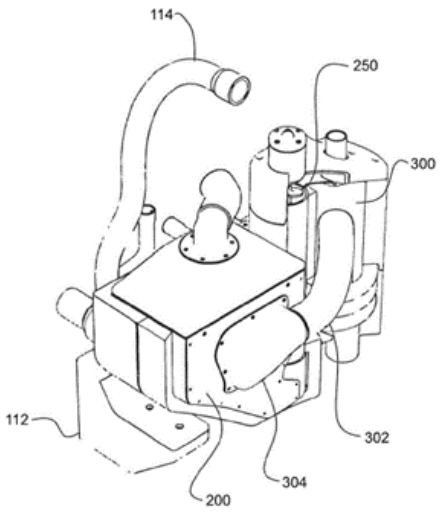


Fig. 4

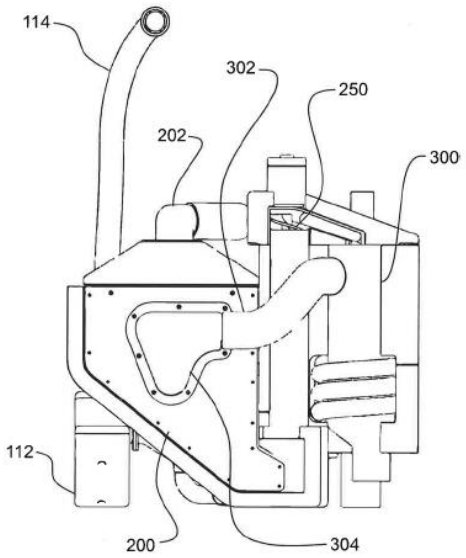


Fig. 5

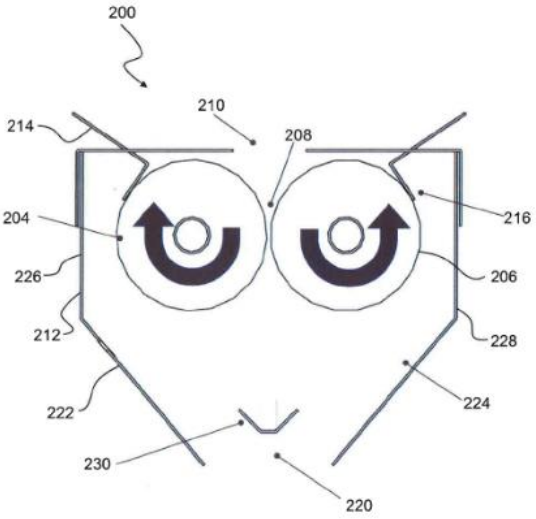


Fig. 6

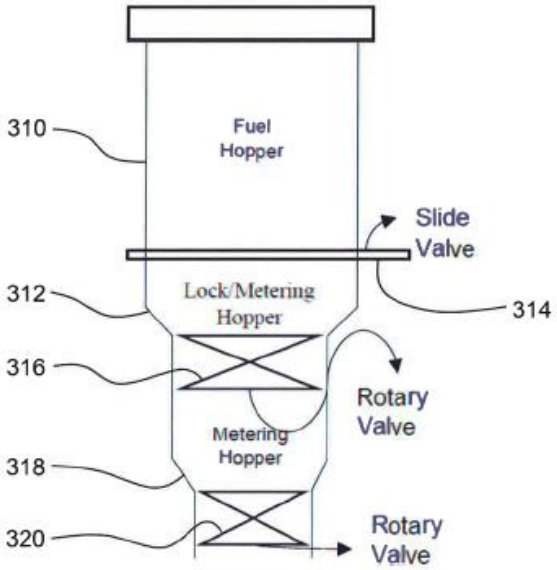


Fig. 7

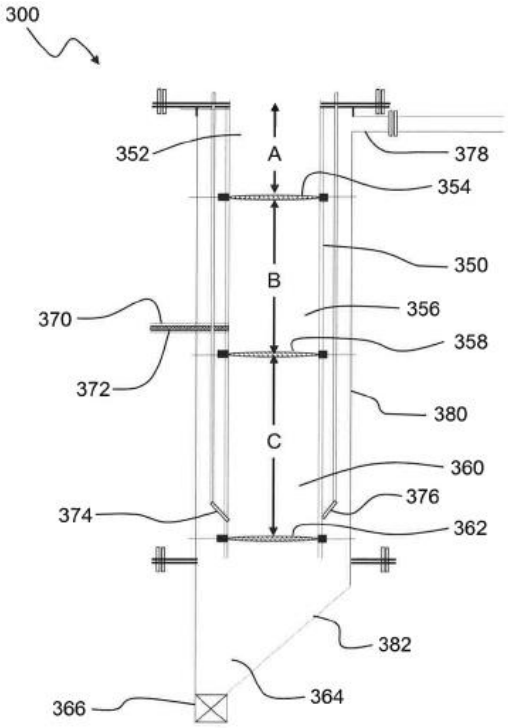
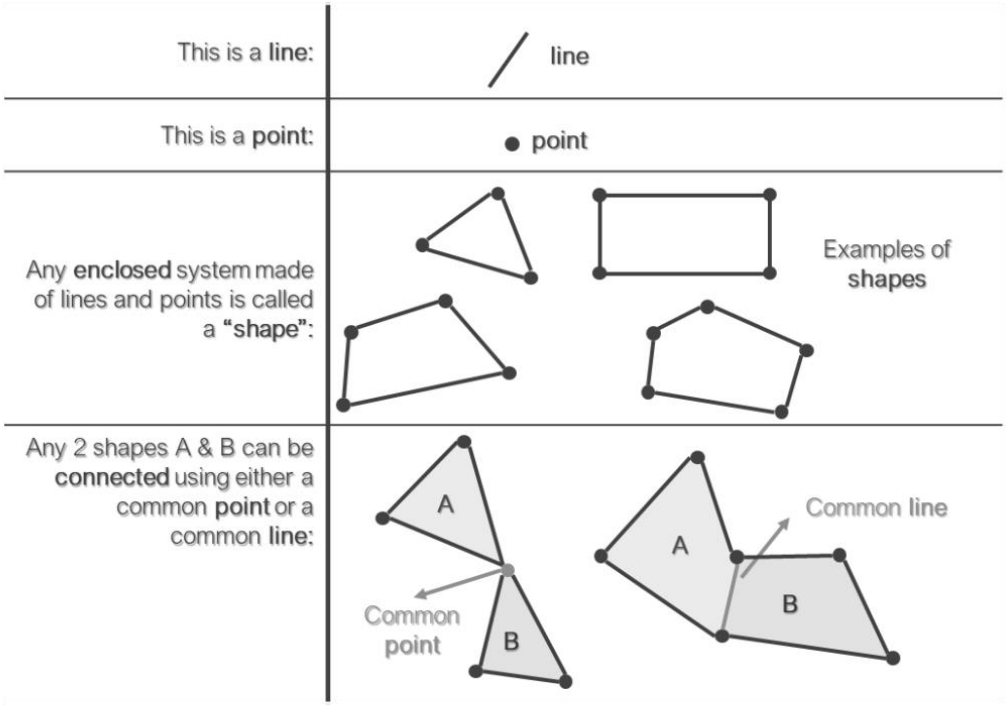


Fig. 8

APPENDIX D – Generativity Test

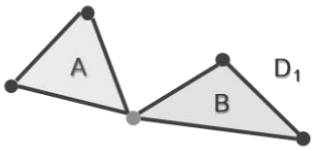
Basic Principles for Task 1



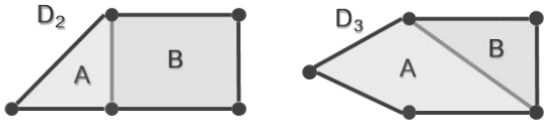
Practical example 1: Creating a shape

- Create 2 connected shapes A & B.
- You can use **exactly** 6 lines and 5 points in total, for both shapes.
- Clearly show A, B.
- Draw as many solutions as possible, naming them as D_1, D_2,…etc.

Example solutions:



In D_1, A & B are connected using a common point



In D_2 and D_3, A & B are connected using a common line

3

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Task 1 (25-30')

- Create 3 connected shapes A, B & C.
- You can use **exactly 9 lines** and **7 points** in total, for all the three shapes.
- Clearly show A, B & C.
- Draw as many solutions as possible, naming them as D_1, D_2,…etc.
- Feel free to sketch in the boxes provided in the answer sheet.

Answer sheet

1	2
3	4

4

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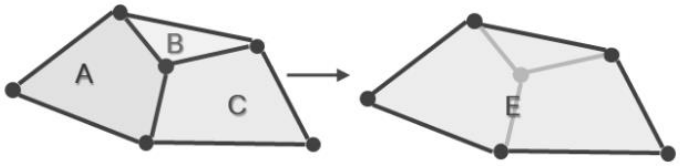
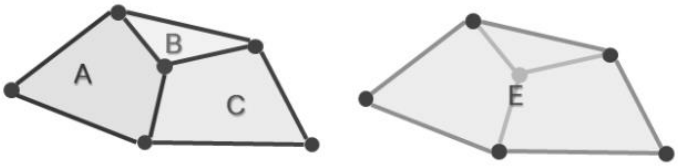
Basic Principles for Tasks 2 & 3

When connected in a way which forms an enclosed system, the shapes form an **"overall shape"**:



Overall shape E

The lines that comprise each shape are called **"outer lines"** of that shape:



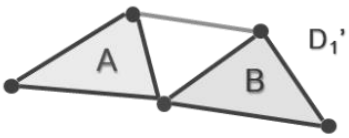
B consists of 3 **outer lines**, while **A** and **C** consist of 4 **outer lines** each

The **overall shape E** consists of 5 outer lines

Practical example 2: Forming shapes

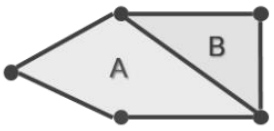
- Keep the solutions of practical example 1 and expand them so that each forms a new shape consisted of <u>one less outer line than in practical example 1</u>.
- You can only add **a maximum of** <u>1 extra line</u> and <u>0 points</u> to each solution.
- Clearly show A & B.
- If the number of outer lines of a solution cannot be reduced, then just redraw it.
- Name the new shapes as D_1', D_2', etc., based on their corresponding initial names.

Example solutions:

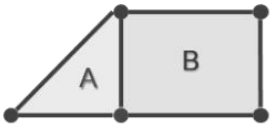


D_1'

D_3' (same as D_3)



D_2' (same as D_2)



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Task 2 (10-15')

- Keep the solutions D_1, D_2, etc. of Task 1 and expand them so that each forms an overall shape D_1', D_2', etc. consisted of <u>one less outer line than in Task 1</u>.
- You can only add a maximum of <u>1 extra line</u> and <u>0 points</u> to each solution.
- Clearly show A, B & C.
- If the number of outer lines of a solution cannot be reduced, then just redraw it as it is.

Answer sheet

1	2
3	4

8

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Task 3 (10-15')

- Keep the solutions (overall shapes) D_1', D_2', etc. of Task 2 and change them so that they form a new overall shape, where A, B & C have at least **4 outer lines** each.
- You are only allowed to add a maximum of **1 extra line** and **1 point** to each solution.
- Name the new overall shapes as D_1'', D_2'', etc. Shade to clearly show A, B & C.
- The number of **outer lines** of the **overall shape** must remain the same as in Task 2.

Answer sheet

1	2
3	4

11

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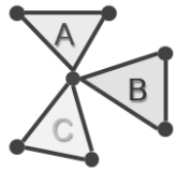
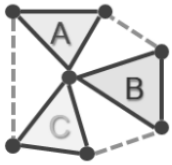
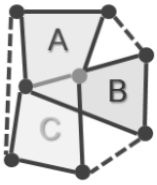
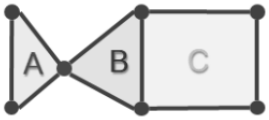
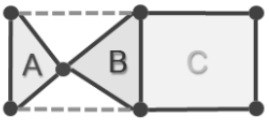
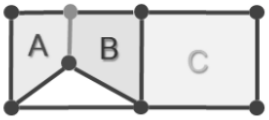
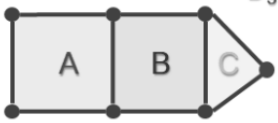
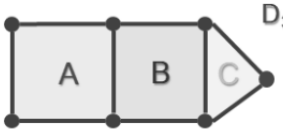
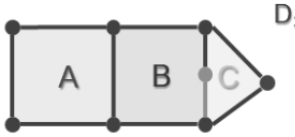
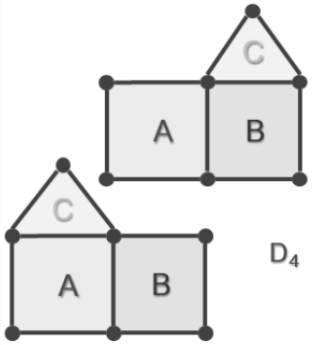
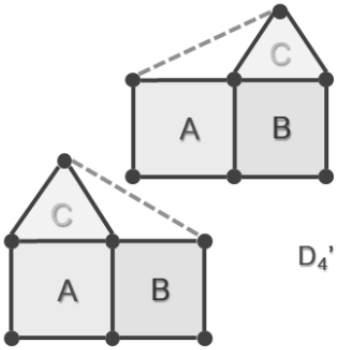
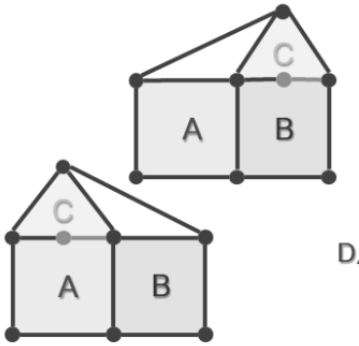
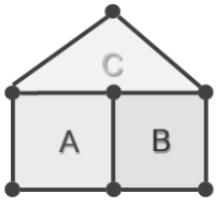
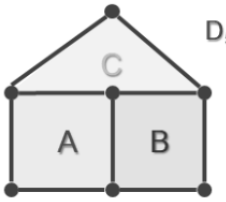
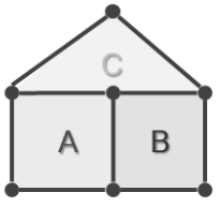
List of known solutions

TASK 1	TASK 2	TASK 3
D_1 	D_1' 	D_1'' 
D_2 	D_2' 	D_2'' 
D_3 	D_3' 	D_3'' 
D_4 	D_4' 	D_4'' 
D_5 	D_5' 	D_5'' 

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List of known solutions

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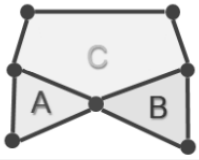
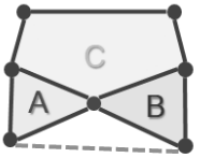
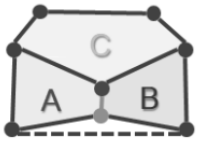
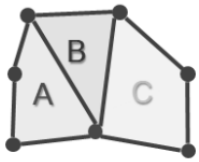
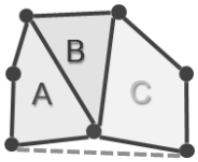
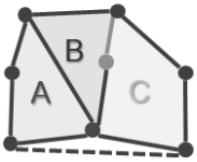
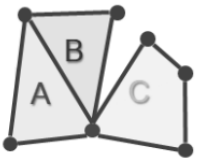
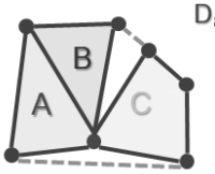
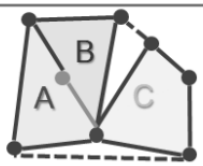
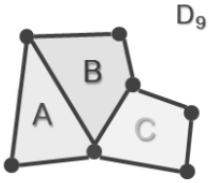
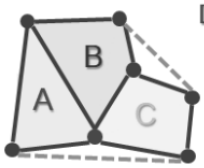
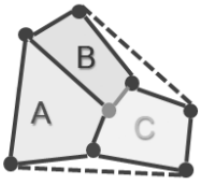
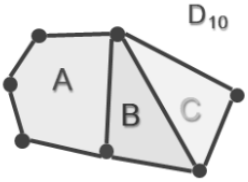
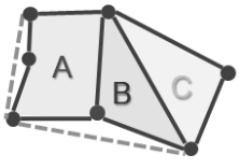
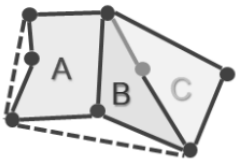
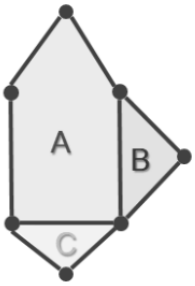
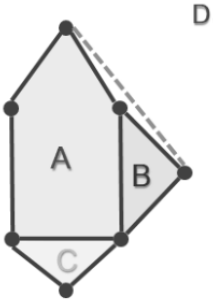
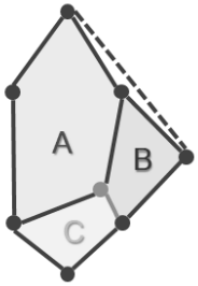
 D_6	D_6' 	D_6'' 
D_7 	D_7' 	D_7'' 
D_8 	D_8' 	D_8'' 
D_9 	D_9' 	D_9'' 
D_{10} 	D_{10}' 	D_{10}'' 
D_{11} 	D_{11}' 	D_{11}'' 

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List of known solutions

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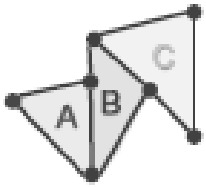
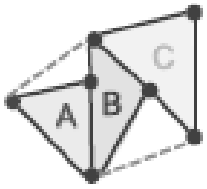
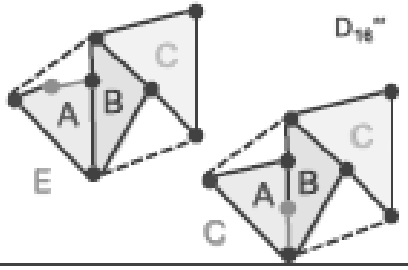
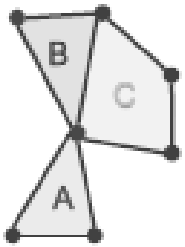
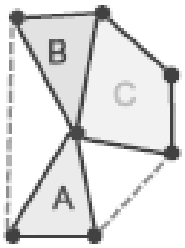
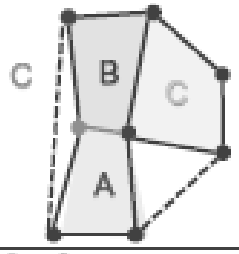
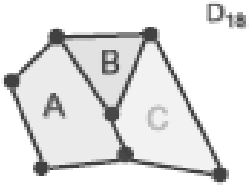
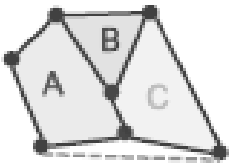
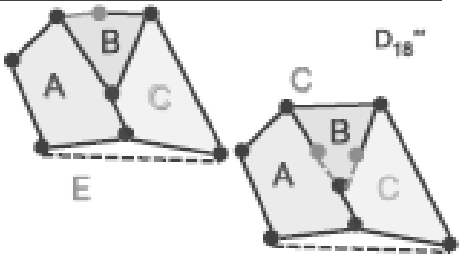
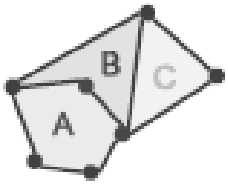
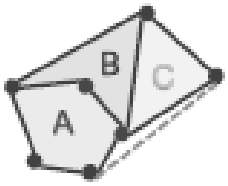
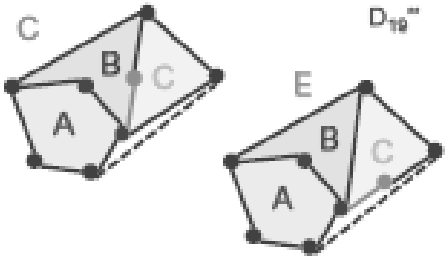
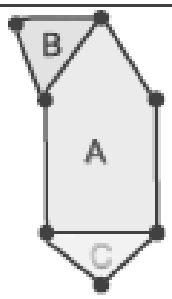
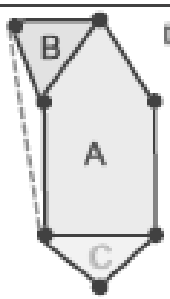
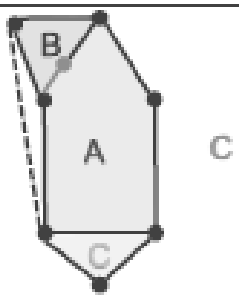
D_{16} 	D_{16}' 	D_{16}'' 
D_{17} 	D_{17}' 	D_{17}'' 
D_{18} 	D_{18}' 	D_{18}'' 
D_{19} 	D_{19}' 	D_{19}'' 
D_{20} 	D_{20}' 	D_{20}'' 

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List of known solutions

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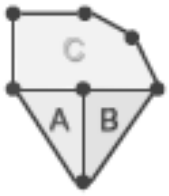
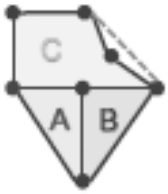
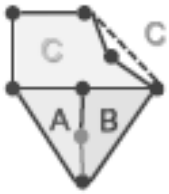
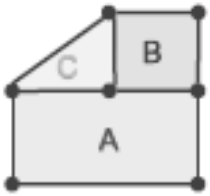
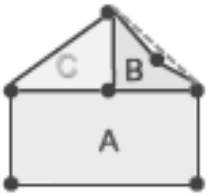
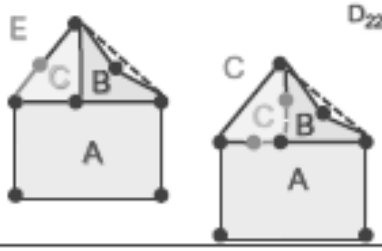
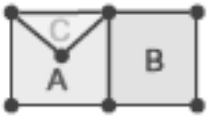
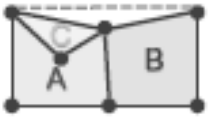
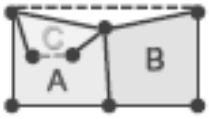
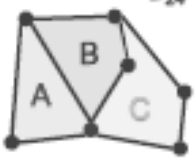
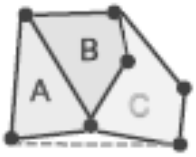
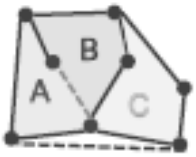
D_{21} 	D_{21}' 	D_{21}'' 
D_{22} 	D_{22}' 	D_{22}'' 
D_{23} 	D_{23}' 	D_{23}'' 
D_{24} 	D_{24}' 	D_{24}'' 
D_{25}	D_{25}'	D_{25}''

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APPENDIX E – Work ethics approvals

PROTOCOL

Gates Foundation Reinvent the Toilet Challenge: DRYER DEVELOPMENT AND TESTING

1. Recruitment and Consent

As per ethics application 2310/2017, submitted by Dr Dani Barrington

2. Study methodology

2.1 Sample Collection and Storage

Sample collection and storage as per ethics application 2310/2017, submitted by Dr Dani Barrington

2.2 Testing Procedure

The testing procedure of the dryer includes the following steps:

- Sample mass measurement using a weighing scale (around 35g of faecal matter and 30-60ml urine for each cycle)
- Mixture is poured into the dryer
- The mixture is heated on the rollers located in the dryer for around 30min at 105°C-150°C using the heat provided by a heat gun or another air-heating device
- The dried sludge is scraped off at regulated intervals (every 5 min)
- The dried 'flocs' that derive are collected
- The dried matter is put in the oven at ≥105°C for 24 hours, preceded and followed by mass measurement in order to identify its moisture content

2.3 Sample Disposal

Sample disposal as per ethics application 2310/2017, submitted by Dr Dani Barrington

3. Data analysis

As per ethics application 2310/2017 for collection and disposal, no personal details of the volunteers are going to be retained.

The purpose of the testing procedure is to identify the changes in the moisture content of faecal sludge over time. The plotted graphs produced will demonstrate the time intervals on the x-axis and the corresponding moisture contents on the y-axis. The moisture content of the input mixture is also important so each input is going to have a different moisture content and density in an attempt to simulate as many classes of the Bristol Stool Chart as possible.

The rheology of the faecal sludge is another crucial factor as we need to identify issues such as clogging or failure of the device to process a particular type of sludge. This can only be tested using visual methods (observation, photographs or video recordings of the process).

Any key findings deriving from the data analysis will allow us to prove or disprove the concept and make the required changes on the next design.

4. Dissemination of information

As per ethics application 2310/2017, submitted by Dr Dani Barrington

5. Ethical issues arising

As per ethics application 2310/2017, submitted by Dr Dani Barrington

6. Data protection issues

I will be responsible for the storage of consent forms (in a locked drawer in the CWSI) and eventual destruction of the data.

STUDY INFORMATION SHEET

Gates Foundation Reinvent the Toilet Challenge: anonymous faeces and urine donations (sample collection type 1)

The purpose of this document is to provide you (the Volunteer) with enough information to assist you in making a decision to take part in this study. If this document does not answer your questions to your satisfaction, please do not hesitate in contacting KONSTANTINOS KENTROTIS (k.kentrotis@cranfield.ac.uk) the researcher overseeing the study.

Introduction

The development of a novel self-contained nano-membrane toilet is underway that discharges pathogen free water and solids intended for use as fuel. Designing the processes within the toilet is dependent on data related to the behaviour of human faeces and urine, the separation of the solid and liquid portions, and the resulting treatment of the solid and liquid portions. The components of the toilet require testing with real human samples to aid design development.

We require faeces and urine from healthy volunteers to characterise and for use in testing certain components of the toilet on human samples. All samples will be anonymous and all experiments will generate generic data not attributable to volunteers. When the experimental tests are completed, any remaining faeces and urine will be disposed of into a biohazard bin, a toilet, or incinerated.

Key points

- The collection process is private, anonymous, and non-intrusive.
- There is no limit to how many times you can donate over the sampling period, so please contribute as many days as you are able.
- There will be plenty of information sheets and volunteer consent forms available in the sampling room, so you can turn up there and read any of the information you like before (or during!) your donation. Just please remember to fill in a volunteer consent form and drop in the box titled ‘filled forms’ in the sampling room – you only need to fill in once no matter how many times you donate.

Recruitment Criteria

Volunteers must be consenting adults aged over 18 studying or working at Cranfield University.

What you will be asked to do

You will be provided with a sample collection kit comprising of:

- A pair of laboratory gloves
- A cardboard collection bowl for faecal matter – these are large enough to sit within a conventional toilet seat
- A 500 mL plastic container with wide mouth screw lid for urine collection
- Black plastic bags – two – one for storage of faecal samples, and one for disposal of the gloves
- Zip ties to secure both the sample bags and refuse bags (containing gloves)
- Information and instruction sheet, a copy of the Bristol stool chart (Figure 1), plus labels and a pen

VOLUNTEER CONSENT FORM

Title of Project: ***Gates Foundation Reinvent the Toilet Challenge: anonymous faeces and urine donations (sample collection type 1)***

Centre: **Cranfield Water Science Institute, Cranfield campus.**

Name of Researcher: KONSTANTINOS KENTROTIS +44(0)7923564851
Name of Research Supervisor: DR. MATT COLLINS +44 01234 752141

(Please tick box)

1. I confirm that I have read and understood the information sheet that has been provided for the study named above. I can confirm that I have been given opportunity to ask questions regarding the study, and that they have been answered to my satisfaction. ☐
2. I understand that my participation in this study is entirely voluntary, and I am free to withdraw my participation at any time without giving any reason, but also acknowledge that once samples have been given, retrieval will not be possible and data collected from samples already donated will still be used as they cannot be connected to a specific donor. ☐
3. I agree to take part in the above-mentioned study. ☐

……	……	……...…
Name of volunteer	**Date**	**Signature**

……	……	……
Researcher	**Date**	**Signature**

Optional:

If you would like to receive a copy of the results arising from this study, please provide your email address below:

.....@cranfield.ac.uk

Contact Information

Researcher: KONSTANTINOS KENTROTIS
PhD Researcher in Environmental Technology
k.kentrotis@cranfield.ac.uk
+44(0)7923564851

Research Supervisor: DR. MATT COLLINS
Lecturer in Breakthrough Innovation
matt.collins@cranfield.ac.uk
+44 01234 752141

PROTOCOL

Generativity Test

1. Recruitment and Consent

Volunteers will be recruited as described in section 2.1. All participants will sign the consent form attached.

2. Study methodology

2.1 Selection of participants

Volunteers will consist of colleagues, students, friends and relatives as the test requires a wide range of disciplinary backgrounds, ages, etc. to be validated. A number as close to 100 as possible will be approached.

2.2 Testing Procedure

The testing procedure of the test includes two methods of answers acquisition:

- A testing phase in a controlled environment in the lab (to ensure that the independent variables are the same) – Mainly for colleagues and students.
- Collection of responses via email, corresponding to tests sent out via email – Mainly for friends and family who live abroad.

A correlation of results between the two methods will be attempted to make sure that the second method can be considered as valid.

3. Data analysis

An example correction template is as follows:

Coextension score: 1 point for each coextension

Fluency: 1 point for each correct solution in any task

Flexibility: 1 point for every distinct solution provided in Task 1

Originality: 3 points for any unique solution among all participants

1 point for any solution which is present in less than 20% of the participants

0.5 point for any solution which is present in less than 50% of the participants

Test No. 1				
Task 1	**Task 2**	**Task 3**	**Extensions**	**Solutions**
6 correct designs	6 correct designs	2 correct designs	2	D_4, D_4', D_4'' D_5, D_5' D_6, D_6' D_7, D_7' D_8, D_8', D_8'' D_9, D_9'
Fluency	**Flexibility**	**Originality**	**Coextensions**	
14	6		1	

This is also the format in which the answers will be saved and stored for a period of maximum 6 months. The data will be deleted after this time. There is no way of matching each test to specific participants or their personal details.

Note: For the needs of the test, each distinct (among all participants) solution needs to be recorded and a unique name will be assigned to it (see "Example Answers" form). This is needed to calculate originality score.

4. Data protection issues

I will be responsible for the storage of consent forms (in a locked drawer in my office for the printed handouts and in a code-protected hard disc for the digital responses) and eventual destruction of the data.

VOLUNTEER CONSENT FORM

Title of Project: ***Generativity test: an attempt to better understand the design technique of coextension***

Centre for Competitive Creative Design, Cranfield campus.

Name of Researcher: KONSTANTINOS KENTROTIS +44(0)7923564851
Name of Research Supervisor: DR. MATT COLLINS +44 01234 752141

(Please tick box)

1. I confirm that I have read and understood the information sheet that has been provided for the study named above. I can confirm that I have been given opportunity to ask questions regarding the study, and that they have been answered to my satisfaction. ☐
2. I understand that my participation in this study is entirely voluntary, and I am free to withdraw my participation at any time without giving any reason, but also acknowledge that once samples have been given, retrieval will not be possible and data collected from samples already donated will still be used as they cannot be connected to a specific donor. ☐
3. I agree to take part in the above-mentioned study. ☐

……	……	……...…
Name of volunteer	**Date**	**Signature**

……	……	……
Researcher	**Date**	**Signature**

Optional:

If you would like to receive a copy of the results arising from this study please provide your email address below:

…….

Contact Information

Researcher: KONSTANTINOS KENTROTIS
PhD Researcher in Environmental Technology
k.kentrotis@cranfield.ac.uk
+44(0)7923564851

Research Supervisor: DR. MATT COLLINS
Lecturer in Breakthrough Innovation
matt.collins@cranfield.ac.uk
+44 01234 752141

APPENDIX F – Published/Accepted work

Design and Science in complex problem solving: more alike than different?

Abstract

The scientific and design methodologies are widely considered polar opposites. This can be particularly felt in organisations when working in multi-disciplinary teams, where differing methodologies are often viewed as incompatible. Yet both can be underpinned by similar levels of rigour and each can provide an equally valid, but different, route to solving a real-world problem. Theoretical explanations of why these approaches present similarities are not clearly understood. This paper reviews how science and design are similar in the context of problem-solving activity. It then suggests that when it comes to complex problem solving, the similarities between the two approaches are maximised.

Keywords: *design problems; design theory; epistemology; philosophy of design*

The relationship between science and design models and methods has always been regarded as problematic (Cross, 1993a; Cross, 2001). Whilst it is difficult to argue with the logic and argument of the established scientific approach, our research shows that design approaches can be underpinned by their own unseen rigour. In addition, researchers have already identified that even the most apparently scrupulous scientific methodologies often entail arbitrary and subjective decisions in the experimental planning stage (Cash et al., 2016; Huberman, 1987; Robson and McCartan, 2015). Wisdom (1974) emphasises that good scientists employ inventiveness and imagination when doing science, claiming that an algorithmic way of thinking and acting is not enough to differentiate sciences (either natural or applied) from other disciplines. After all, some of the greatest scientists have been acknowledged for their unconventional and creative problem-solving skills. For example, we can refer to Kekulé's dream of the benzene ring, Einstein's visual thinking which led to the general theory of relativity and Feynman who got inspired to create the Feynman diagrams by a wobbling plate with a Cornell logo on.

The beginning of an ongoing effort to make design more 'scientific' was marked in the 1960s by the foundation of what is now known as 'the design methods movement'. This effort not only has had little or no success until now, but has instead made the

differences between the two disciplines even more apparent (Cross, 1993a; Huppatz, 2015). A key difference indicates that designers (and engineers) have to solve problems which are often characterised as 'complex' or 'ill-structured', whilst natural science deals more with 'well-structured' ones (Jonassen, 2000; Simon, 1969). A research question that naturally derives, is whether the problem-solving approach that designers follow is in reality different than the ones followed in other disciplines.

This paper initially reviews the similarities and differences between design and science by focusing on problem-solving. Based upon the insights gained, it then attempts to propose that the design problem-solving approach might be more suitable for complex problems and that in this particular case, the similarities between the design and the scientific approaches are more apparent than in any other.

1. Background

1.1 Science and design: a literature review

It is a common belief that design and science are fundamentally different (Giaccardi and Fischer, 2008) and there are many views from the literature on the differences and commonalities between the two disciplines. Willem (1990) implies that design is concerned with all human-made objects. Similarly, Cross (1984) describes science as the discipline which "studies the natural world" and design as the one studying "the man-made world". Simon (1969) established the view that design is conceived as the field that examines "how things ought to be" and science as the one that studies "how things are". Buchanan (1992) argues that design is about conceiving or planning what does not yet exist, whilst science is about understanding the universal properties of whatever already exists. Skolimowski (1966) describes design (namely 'technology') as the discipline that creates reality according to human design and science as the field that investigates the given reality. Similar to this approach, Heylighen et al. (2009), based on Searle's (2001) theory of the 'direction of fit', parallelised design with the 'world to mind fit' and science with the 'mind to world fit'. In other words, design attempts to fit the designed artefact to the world whilst science attempts to fit the truth of the world into the human mind. Galle and Kroes (2014) claim that design and science aim at different things: the first aims at the production of artefact proposals and the latter at the production of theoretical knowledge.

The process of design reasoning is often perceived as abductive, in contrast to the

inductive reasoning that science follows (Dorst, 2011; Cross, 1999). Another well-established idea, also introduced by Simon (1969) and revisited by later studies (Lawson, 1979), is that design problem-solves by synthesis, combining ideas into a complex whole, in opposite to the traditional scientific analytical thinking.

Despite these distinctly held viewpoints, others point to the similarities. Holmström and Ketokivi (2009) argue that whilst design and science may have different aims, they both constitute intelligent problem-solving activities and as such will have much in common. Their view reflects on the idea of Popper (1999), who also remarks that all activities in life are about problem solving and therefore resolve into the same action. They argue that 'the world' is the common subject matter between science and design, but acknowledge that a methodological difference exists; thus the criteria upon which the outputs of the two fields are evaluated are different. Holmström and Ketokivi (2009) also highlight an ontological difference between the two, describing design as an exploratory research discipline and science as an explanatory one. Farrell and Hooker (2012) stress that design produces an artefact as the product of its research, whilst science does not produce the natural world. They, however, support the view that despite design and science being two different purposive activities, they share a common cognitive process.

Tables 1 summarises the significant differences and commonalities, identified from the literature, between science and design.

Table 1. *Differences and similarities between design and science, as found in the literature.*

THEME	DESIGN	SCIENCE	REFERENCE
Area of Interest	Human-made objects	Natural world	Willem (1990)
	How things ought to be	How things are	Simon (1969)
	Conceiving and planning things that do	Understanding the universal properties of what is	Buchanan (1992)
	Creates reality according to design	Investigates given reality	Skolimowski (1966)
Philosophy	World to Mind fit	Mind to World fit	Heylighen et al. (2009)
	Practical-Prescriptive	Cognitive-Descriptive	Galle and Kroes (2014)

	Exploratory	Explanatory	Holmström and Ketokivi (2009)
Aim	Aims at production of tangible proposals	Aims at production of theoretical knowledge	Galle and Kroes (2014)
	Artefact as end product	Does not reproduce the natural world as its end product	Farrell and Hooker (2012)
Reasoning/ Logic	Abductive	Inductive	(Dorst, 2011)
	Synthetic	Analytical	(Simon, 1969; Lawson, 1979)
Problem-solving	Both are intelligent problem-solving activities and thus it is only natural that they have things in common		Holmström and Ketokivi (2009)
Subject Matter	They have the same subject matter: 'the world'		Holmström and Ketokivi (2009)
Cognitive Process	They share a common cognitive process		Farrell and Hooker (2012)

What the literature tells us is that design and science differ in principle, regarding their aim, philosophy, reasoning and object of investigation. Given these differences, it is often assumed that their methods also differ accordingly. Furthermore, a common idea often discussed in the literature is that any difference between the ways that designers and scientists approach problems is rooted in this methodological difference. This hypothesis is challenged below.

1.2 The Scientific and the Design method

Mantell (1974) defines the scientific method as a "time-based tested broad pattern of problem solving which gives efficient results". Feynman in one of his famous physics lectures at Caltech explained how the scientific method works, meaning how scientists attempt to solve a problem (Feynman et al., 1963). Surprisingly enough, according to Feynman, it all starts with a "guess", which comes from one person's innate or acquired

knowledge. Simon (1977) emphasises this role of heuristics and the existence of "highly selective" processes in the organisation of problem-solving theory. The scientists see a phenomenon that is still unexplained and make guesses of why this could happen. Then each guess is translated into a mathematical set of formulae. This set of formulae now constitutes the hypothesis. Afterwards, the computation of the consequences, should the hypothesis be right, takes place. Finally, observation or experimentation follows: this means that the phenomenon is simulated or reproduced and the results are compared to the computed consequences. If the results obtained from the observation do not agree with the consequences then it is self-evident that the guess/hypothesis was not correct and it needs to be changed. If the results confirm the initial hypothesis, then it still cannot be safely concluded that the guess is right, but it cannot be proven as wrong either. In science, it can never be proven that a theory is definitively right; it can only be assumed that the theory is correct until another theory or result proves it wrong. A classic example of this is Newton's theory of gravitation. This theory was able to describe the phenomenon for centuries, until Einstein came up with the laws of general relativity, which proved that Newton's theory was not entirely right and that it does not work for all possible scenarios. However, we are still taught Newton's theory at school even though it is not 100% correct. The reason for this is simple: it can still give essentially accurate results for the problems that we face in most real-world scenarios.

The design method does not differ in principle. After identifying the right question for a problem, designers attempt to address it with a 'guess', e.g. their design proposal as the same starting point as scientists. Their 'guess', which constitutes their hypothesis, is then tested in the form of prototypes. If the proposed idea survives the prototyping and testing process, it becomes the best 'solution' until it is essentially superseded.

In design, as in science, designers' work can only be proven 'wrong' if it fails to fulfil its design, but it will never be 100% right. This last view was introduced by Simon (1969) and it was widely accepted by the second-generation design methods of the early 1970s, which recognised the existence of appropriate solution-types and the participatory process where designers co-exist and co-operate with the problem "owners" (Cross, 1993b). Design artefacts' life cycle, just like the one of scientific theories, ends when another, which serves the problem owners better, appears.

It can thus be argued that there is a form of equivalence between the three main stages of the scientific and the design method. Figure 1 illustrates this equivalence.

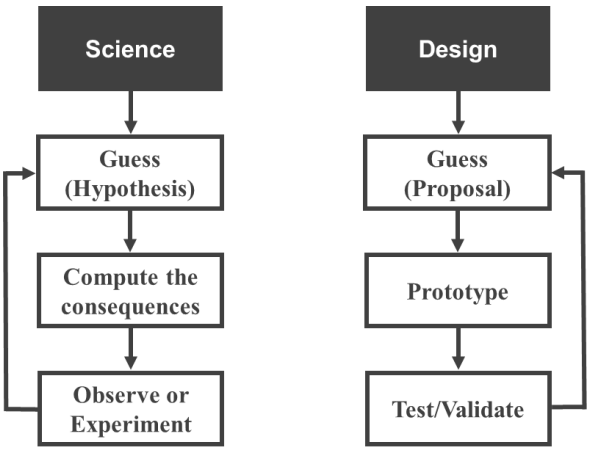

Figure 1. *The equivalence between the scientific and the design method*

There has been a long discussion between Farrell and Hooker on one side and Galle and Kroes on the other (Farrell and Hooker, 2012; 2013; 2014; 2015; Galle and Kroes, 2014), regarding whether science and design are "identical twins", if they are totally different problem-solving methods or whether they at least share a common (and rigorous) cognitive process. The equivalence presented above suggests that each method has considerable similarities in terms of the logical path they follow, from the idea generation to the idea validation phase. Any distinction between the two methods should only be then due to the different nature of the idea or 'guess' which triggers the rest of the process. This can be cross-verified by past studies which have found that there is a difference in the solution types proposed by scientists and designers (Lawson, 1979). More precisely, designers' strategies have been identified as solution-focused and synthetic, whilst scientists' ones as problem-focused and analytical. In turn, as we all share a common core cognitive process (Farrell and Hooker, 2012; 2013), that of human beings, any distinctive features of design ideas must be due to a difference in the characteristics of design problems. Thus, what should be now reviewed is the type of problems usually encountered in each discipline.

2. Problems

2.1 Well- and Ill-structured problems

A long-lasting tradition in design theory considers and treats design tasks as wicked or ill-structured problems (Buchanan, 1992; Coyne, 2005; Kunz and Rittel, 1972; Rittel and Weber, 1973). Wicked or ill-structured problems are problems where many factors or stakeholders interact with each other in a confusing way, information is unclear and their exact structure remains partly or wholly undefined (Churchman, 1967; Simon, 1977). This definition was first introduced by Simon in 1969, and much of the contemporary work in design research still remains aligned with his perception of design as a rational problem-solving activity of ill-structured problems (Dorst, 2006). The reason why design problems are characterised as such, is because they have ambiguous specifications of goals, no determined solution path and the need to integrate multiple knowledge domains (Reitman, 1965; Simon, 1973).

Whilst Simon's attempts to unify design with the rest of the sciences by using problem solving as a link, might still constitute a popular theory in design methodology, they have proven fruitless in the course of time, rendering the differences between the disciplines even more obvious (Huppatz, 2015). This outcome confirmed Alexander's (1964) claims that mathematical logic has limitations when it comes to solving design problems (Dorst, 2006). Rittel and Weber (1973) suggested that this is mainly because design problems belong to the same category as political or social problems and therefore they "cannot be solved", but only "resolved". Their theory contradicted Simon's thesis (1973) that ill-structured problems can become well-structured with practice and experience, as it implies a deeper and non-bridgeable distinction between the two types of problems.

Recent studies focusing on the problem typology (Jonassen 1997, 2000, 2004, 2007; Jonassen and Hung, 2008) have gone one step further, classifying the types of problems that exist in all disciplines based on six main criteria: learning activity, inputs, success criteria, context, structuredness and abstractness. Much of this work is articulated by Jonassen's (2000) typology of problems which presents a spectrum from the best-structured to the most ill-structured ones. Each type of problem is different regarding its cognitive, affective and conative process. An attempt to link this work on the typology of problems with the previous discussion concerning the disciplinary characteristics is illustrated in Figure 2.

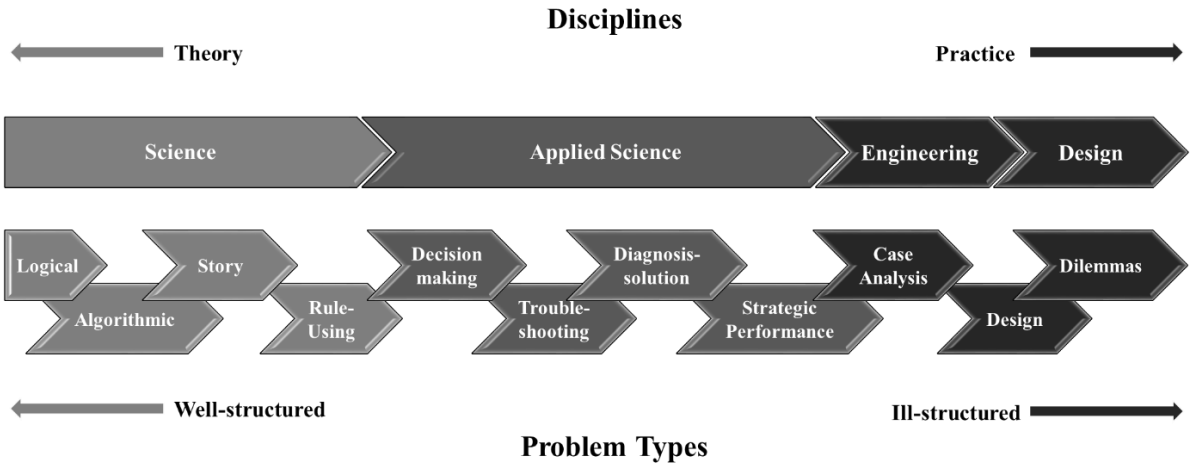

Figure 2. *A depiction of how different problem types correspond to different disciplines, by extending Jonassen's (2000) problem typology*

There seems to be a correlation between science, theory and well-structured problems on one end, and design (including engineering), practice and ill-structured problems on the other end.

2.2 Complexity and complexity limits

There have always been problems characterised by complexity. By the term 'complex', we usually refer to problems which are characterised by many variables involved, a large number of sub-problems required to be solved, or a high level of stochasticity. If we break them down, into many different smaller problems, we might be able to discover laws which fully or partly describe many individual pieces of the problem, but are very unlikely to find a set of laws which describes, or unifies, them all (Grabowski and Strzalka, 2008).What needs to be clarified at this point is the difference between the term 'complex' and the term 'complicated'. Complicated is a problem that requires a lot of analysis but which can still be broken down into many solvable problems (Glouberman and Zimmerman, 2002). Going further, we could argue that a complex problem can be broken down into a number of simpler (and therefore solvable) problems and a number of complex ones (still unsolvable).

The technological progress and more precisely the rapid advancement of computing, communication, control, information and sensor technologies, has resulted in new dynamic systems, which are characterised by high levels of complexity (Cassandras and Lafortune, 2008). The problems that scientists and engineers have earlier faced, could be adequately modelled based on the theories of classical and non-classical mechanics,

gravitational laws, physical chemistry and so on. The reason is that these problems deal with continuous, time-based quantities and variables such as velocity, acceleration, displacement, gas or fluid flow rate, and pressure. By the term 'continuous', we refer to quantities which take real values as time continuously evolves, and can thus be adequately modelled by ordinary and partial differential equations. However, contemporary problems deal with human-made, dynamic systems which can hardly be described by continuous and time-based variables (Cassandras and Lafortune, 2008). A fact that emerges is that in the past, complexity used to refer more to the size of systems, whilst nowadays, it also arises from the interaction between the underlying rules and structures.

There are three basic complexity limits echoing the fact that was described above, namely that the direct solution of various problems is almost impossible using conventional methods. The first limit, known as the "central limit theorem", indicates that we cannot learn faster than $1/\sqrt{T}$ from a data set, where T is the time spent to collect or simulate the data. The second one, known as the "NP-hard" limit, indicates that there is a class of problems that, due to their nature and given the current computational capabilities, we cannot solve in polynomial time, meaning in intuitively short time. Finally, the colloquially called "No-Free-Lunch Theorem" (Wolpert and Macready, 1997) quantifies the trade-off between the generality and the efficiency of an algorithm. That means that if there is a method or technique to solve a problem efficiently given specific constraints and resources, then this method is very limited in terms of the amount of problems it can solve. The three complexity limits are a reminder that there are problems that engineering and science still struggle to solve and a new perspective is therefore needed. Managing to overcome the constraints set by these limits will enable us to solve complex problems in the fields of optimisation, traffic control, automation, manufacturing systems and big data (Cassandras, 2017; Cassandras and Lafortune, 2008).

What is now left to link is structuredness to complexity. From the analysis of well- and ill-structured problems depending on their inputs (variables) and outputs (success criteria), it is clear that complexity increases according to the ill-structuredness of the problem. In Figure 2, for example, simpler problems would be placed towards the end of well-structured problems and complex problems towards the other end of the spectrum. This does not imply that there are not logical or algorithmic problems that are characterised by complexity, but as previously discussed, the structural or dynamic

complexity is a different one than the one referring to the size of the problem or the computational resources that are needed to solve it.

3. The Design approach to complex problems

Analytical (convergent) thinking is believed to be one of the essential features of scientific methodology. It is based on the principle that if a complex problem is broken down into many smaller problems, then, after a number of steps, the problems that derive are simple enough, to find their solutions. Referring to the definitions of complex and complicated problems given above, we could argue that a complex problem can be broken down into a number of simpler (and therefore solvable) problems and a number of complex ones (still unsolvable).

Design thinking, on the contrary, has a more holistic (divergent) approach. It sees the problem as an entity and places it in its wider environment. This way it can be easier to think of alternatives to solve the problem. Friedman (2003) describes a designer as a "synthesist" aiming to solve problems and a "generalist" able to appreciate the wide range of skills and talents required to come up with solutions. He also highlights that this synthetic nature of designers is even more necessary in today's complex organisational and technological environments, where designers need to work in several levels and to lead problem-solving groups (Friedman, 2003). Design deals with the question why the problem is there in the first place, whilst science analyses it and breaks it into pieces until one of those pieces gives the answer. Following strictly the analytical approach, is like searching for a solution within the problem and therefore this can only give results in a reasonable amount of time and effort and only if the problem is, at worst case, complicated. But what if the problem is complex up to the extent that its sub-problems are still complex and not solvable by the analytical approach? In that case, it is like being trapped in vicious circle out of which the answer might never come. However, Figure 2 shows that there might be a solution out of this infinite loop using design thinking. This may be why design thinking has become a popular practice for complex problem solving (Dasgupta, 2003; Hertenstein et al., 2013).

As a result, we could now assume that if the analytical approach fails to give an answer to a problem due to its complex nature, in a finite number of steps and using a finite number of resources, then the holistic approach that design offers could provide a

solution, which, however derived, must have more validity than no solution at all. Thus, the scientific and design approaches are potentially highly complementary to each other.

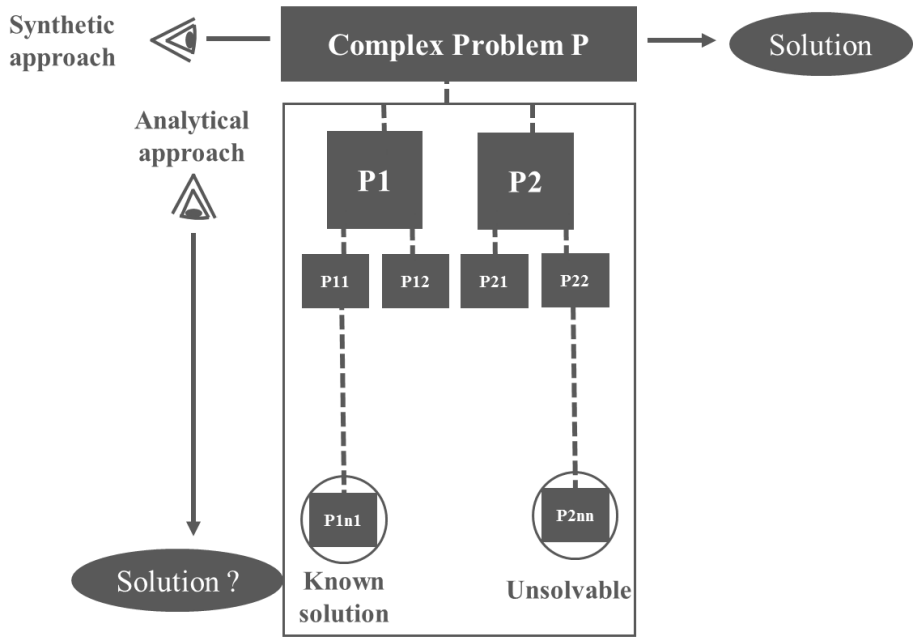

Figure 4. *The synthetic versus the analytical approach in problem solving*

Let us, for example, suppose that we are given the following 3rd degree equation: $x^3+3x^2+2x+1=0$ (Eq. 1) and that we are looking for its real solutions ($x\epsilon R$). How would a mathematician attempt to solve this problem? If we wanted to arrive at a solution following the strict mathematical approach, we would need around 9 complicated and difficult steps (Table 2). The question arising is how would someone, without the required background knowledge of all these steps and transformations, approach the same problem? If Eq. (1) is named as f(x), then a simple approach would be to start trying different values for x and see what f(x) generates until a change of sign is noticed. This is known as the Bolzano's Theorem (Apostol, 1967), but those who use it can do so without ever knowing of the theory, only that it is a seemingly logical approach. Table 2 illustrates these different approaches and the number of steps required for each one.

Table 2. *The 'conventional' and the 'simplistic' method of solving the problem.*

'Conventional' Method	'Simplistic' Method
1. $x^3+3x^2+2x+1=0$	**1.** $f(x)=x^3+3x^2+2x+1$
2. $x^3+\alpha x^2+\beta x+\gamma=0$; $\alpha=3$, $\beta=2$, $\gamma=1$	**2.** $x=2$: $f(2)=25$

<table>
<tr><td>3. x=y- $\frac{\alpha}{3}$=> y^3+px+q=0; p= β- $\frac{\alpha^2}{3}$, q=γ- $\frac{\alpha\beta}{3}$ -$\frac{\alpha^3}{27}$</td><td rowspan="3">x=1: f(1)=7
x=0: f(0)=1
x=-1: f(-1)=1
x=-2: f(-2)=1
x=-3: f(-3)=-5</td></tr>
<tr><td>4. y^3-y+1=0; pq≠0, p=-1, q=-1</td></tr>
<tr><td>5. y=z- $\frac{p}{3z}$=>$\left(z+\frac{1}{3z}\right)^3$ - z - $\frac{1}{3z}$ +1=0=>
w^2+qw - $\frac{p^3}{27}$ =0; z^3=w</td></tr>
<tr><td>6. w_1=-0.039 and w_2=-0.962</td><td rowspan="3">3. A. Interval I=[-2,-3]$\epsilon\mathbb{R}$
B. f continuous function: I→ℝ
C. 0ϵ(f(-2), f(-3)): f(-3)<0<f(-2)
A, B and C=> there is c ϵ(-2,-3) such as f(c)=0</td></tr>
<tr><td>7. $z_1=w_1^{1/3}$ =-0.338 and $z_2=w_2^{1/3}$ =-0.987</td></tr>
<tr><td>8. y=z+$\frac{1}{3z}$ => $y_{1,2}$=-1.325</td></tr>
<tr><td>9. x=y-1=> x≈-2.325</td><td>4. The solution Is in the interval between -2 and -3</td></tr>
<tr><td colspan="2">Note: f(x)=0 has also two complex solutions: $x_{2,3}$ = -0.3376±0.5623i which can be ignored in this example as x $\epsilon\mathbb{R}$</td></tr>
</table>

This example is used as a metaphor to demonstrate that the strict scientific approach often requires a high degree of specific knowledge, which in itself will have required considerable investment in resources, such as time and money for specialised education. The first approach, can be likened to the way in which a scientist would try to solve a problem whilst the second-more practical but simpler-approach, which is based upon nothing more than logic and intuition, could be compared to the path a designer would use to tackle the same problem. As a general rule, scientists possess a strong theoretical background and are characterised by increased specialisation, which allows them to go as deep as they feel is required, whereas designers frequently need to be skilled at solving problems not only across a broad knowledge space, but also across multiple knowledge spaces. To do so, designers have to rely upon simpler logical methods and a high degree of intuition. Referring back to the previous example in Table 2, it is worth noticing that the second approach might not be able to give an exact answer straight away, but it is capable of answering quickly the question 'Does this function have a real root?'. The 'Simplistic Method' also indicates that the interval between -2 and -3 is where we have to look for the solution. The point here is that if this were a real problem, that a scientist or designer had to face, even the answer of whether the problem has a solution or not and a good approximation of it, might be enough to move forward. In that case, no further

effort would be required. On the contrary, following the first approach, if someone failed to go through all the different steps accurately, they would not be able to get this answer. Such differing approaches to real-world innovation scenarios could be manifest as a quick proof-of-concept prototype, by a designer, or a specific experiment from a scientist. The latter being akin to one of the multiple steps in the 'Conventional Method', which may in itself, provide no significant guidance to the scientific team as to whether the direction of travel is correct or not, creating uncertainty and delays.

In summary, increased specialisation tends to indoctrinate people to follow a strict analytical methodology to solve problems, often-ignoring simpler paths, which can lead to the same answer, or at least a satisfactory proportion of it. This constitutes a significant difference between science and design. However, when the nature of the problem is complex, the scientific problem-solving methods tend to approach the ones that designers generally follow. In other terms, someone could claim that in this particular case, science is nothing but a special case of design.

4. Discussion

There are two main considerations to be discussed. The first one relates to the wide held belief (even among the design community) that designers solve ill-structured problems by altering the scope or structure of the problem. In other words, this implies that the provided proposal does not correspond to the original problem definition, hence it cannot be considered as a solution. The best way to respond to this challenge, is by referring to science. Let us consider for example, the superposition theorem, applied in the case of an electrical circuit with two sources (two loop circuit). It is mathematically impossible to try and solve the problem as it is. The only way is to isolate the two sources and solve two different problems, corresponding to the existence of one source at a time. Then, the two solutions are algebraically summed ant the final result derives. One could argue that the original problem is not directly approached, exactly as it happens in the case of the mathematical problem presented earlier. There is only one problem statement asking for a real solution, with no indication about identifying a change in sign between two values $f(x_1)$ and $f(x_2)$. No one can claim though that these approaches are not valid, and even sometimes -due to computational complexity- the only way forward. So, asking the right questions, or slightly changing the scope of the problem is not only a design tactic; it is a

common and efficient approach in science too.

The second consideration is probably even more fundamental than the first one. Strictly speaking, and according to design theory (e.g. C-K theory), problem solving does not concern design. Problem-solving is viewed as the identification of a solution among a set of many possible ones. Design, on the other hand, should be defined as the generation (hence "design") of a new concept ("proposals"). Following this rationale, design should not be linked to problem solving and therefore the topic of this paper lies in a contradiction, from a semantics point of view. Although we acknowledge this consideration, the best way of responding is to remind that even in science, the solutions are often "designed". The construction of the complex numbers can be taken as an example. We invented imaginary (complex) numbers in order to tackle problems, which in real analysis are very difficult or impossible to be solved. Consequently, solutions, or more precisely the theories linking to solutions, are designed even in science. We shall not then stick to a strict, semantical definition of "solution" as something that cannot be designed.

A key message of this paper is that the design method might be able to solve complex problems in science which have similar characteristics to regular design challenges. In order to examine this scenario, the design approach would need to be detached from the scope of design problems and studied as a generally applied method of problem solving. It is not suggested that the design method can solve all non-design problems. On the contrary, if this were the case, scientists would have developed a similar process to tackle their problems, based on their experience and the requirements of the challenges they face. It is, after all, commonly accepted that cognitive processes enable skills and methods to be adjusted based on the type of problems faced most often (Schön, 1987).

Another point that needs to be highlighted is that the results deriving from each study usually rely on terms and notions that are not well-defined in the literature. The term "design" itself, for instance, corresponds to a plethora of professions, methods and practices and each researcher hypothesises a definition or content which relies on their research field or personal experience. As Buchanan (1993) mentions, it is "frightening" to consider the wide range of uses of the term.

The mathematical example presented in the present paper, provides a good analogy for consideration as it feeds both methodologies (the scientific and the design-like) with the

same problem, so that the complexity of the processes, and the results, can be directly compared to each other. Although a single metaphor cannot provide solid grounds upon which an argument be validated, it is hoped that this paper can provide direction for further studies concerning the potential suitability, and rigour, of design thinking for complex problem-solving activities outside of the strict boundaries of the design discipline. In other words, this study suggests that the design approach could stand alone as an equivalent problem solving method to the scientific approach, despite its nature to be more intuitive or experience-based. As an example, a promising theory to tackle the problems created by the technological evolution was introduced in the 1980's and treats such technological systems as discrete and event-based, rather than continuous and time-based. As Cassandras (2017) -one of the founders of discrete event systems theory- claims, there is a way to solve such complex problems by exploiting their special structure, asking the right questions and challenging the conventional methods. Someone could say that this approach is not far away from what designers do when they face a problem. We can, for instance, refer to the fact that designers dedicate a lot of effort and time to make sure that they are solving the right problem.

A last question that needs to be addressed is whether it is fair or valid to compare and examine a 'parallel' complementarity between design and science. The traditional epistemological and technology management theories consider the two of them as distinct disciplines sitting on opposite sides of the same spectrum, facing different types of problems. Although the differences in the nature of the problems that each discipline encounters cannot be refuted, the hypothesis of the present study lies in a scenario where an individual or group combines the scientific knowledge with the design thinking approach, when attempting to solve a problem. In this hypothetical scenario, the centre of attention is not the nature of the problem anymore, but the problem-solving approach.

5. Conclusion

To summarise, it is suggested that there might be particular types of problems, either within or outside of the scientific scope, which may suit better to the way that designers think and approach problems. As previously discussed, there are likely to be problems where a sub-optimal solution, regardless of how it derives or whether it is complete or not, is better than no solution at all. Additionally, there is evidence to support this view,

as multi-factoring and contextual relativistic thinking are considered necessary to solve complex and ill-structured problems.

What has to be highlighted is that the purpose of this paper is not to categorise people into scientists and designers. On the contrary, it is acknowledged that scientific and design thinkers exist in both disciplines, but the focus is drawn upon the dominant and most common approaches or ways of thinking in each discipline.

Since the beginning of the 'design methods movement' in the 1960s, researchers have been trying to make design more 'scientific', with little or no success. With today's ever more complex challenges, now may be the time for designers to feel confident in their "designerly ways of knowing", and for design methodology to be acknowledged for its practical application even outside of the design discipline.

The take away message of this paper is that here are elements in design thinking, which root back in the oldest, simplest and most intuitive ways of solving problems, but which could be proven useful to encounter modern, complex problems. After all, the categorisation into disciplines and problem types is nothing more than a human invention, enabling us to specialise and face each problem more efficiently. Ultimately, the world that surrounds us is one and its problems are there, waiting to be faced, indifferently of existing specialisations and knowledge domains.

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Design and development of a novel drying system for a waterless, self-sustained toilet

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Abstract: *Contemporary western-style toilets require a large quantity of clean water and an integrated sewage system to operate, but 2.3 billion people remain without access to improved sanitation. For this part of the globe's population, a waterless and self-sustained toilet would constitute a solution of high potential. A critical technology for such a toilet is a system of dewatering, drying and pelletizing human*

faeces, as incineration is needed to reduce biomass and to remove pathogens. This paper presents the design and development of a technology for in situ, small-scale faecal sludge treatment. Unlike that of existing industrial dryers, the scope of the technology presented in this paper was restrictive to a limited amount of space and low energy demands. The concept of the novel technology was developed using a rapid, design-led innovation process.

Keywords - *Drying technology, Conceptual design, Design-led innovation, Design process*

I. INTRODUCTION

Cranfield University's Nanomembrane toilet, part of the 'Reinvent the toilet' challenge, set by the Water, Sanitation & Hygiene programme of the Bill & Melinda Gates Foundation, aims to treat human waste on site and to recycle any useful resources without generating hazardous products [1], [2]. The Nanomembrane toilet consists of 7 main technologies. (1) A rotating bowl that receives the urine and faeces, (2) a swipe mechanism, which cleans the bowl and empties mixed sludge in (3) a settling tank. The sludge is then primarily dewatered and transferred via (4) an Archimedes screw. As a next step, (5) a drying device is needed to prepare the material for (6) the combustor, as incineration is required to remove pathogens and to reduce biomass. Finally, the accumulated urine is filtered by a set of (7) nanomembranes, out of which clean water is generated. The overall system is illustrated in Figure 1.

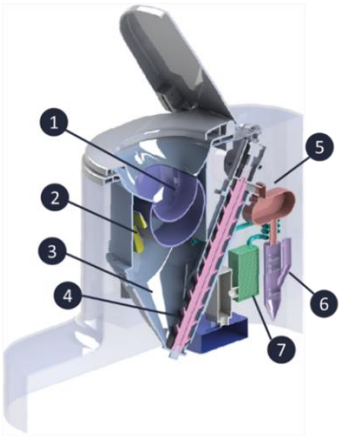


Fig- 35: Cranfield University's Nanomembrane toilet consisted of: 1-Bowl, 2-Swipe, 3-Settling tank, 4-Archimedes screw, 5-Dryer, 6-Combustor, 7-Nanomembranes

The present paper presents the design and development of the 'dryer', a technology which, in reality, constitutes a dewatering, drying and pelletizing system. Its purpose is to decrease the moisture content from around 80 wt.% (percent by weight) down to approximately 20 wt.% and to form small dried pellets of around 1 gram each. The calculations for the exact moisture level of the sludge input were based on internal tests conducted and on Zuma et al.'s work [3], who identified that samples coming from VIP latrines in Durban, South Africa had a median moisture content of 81 wt.%. These findings are close to the ones resulted from Rose et al. [4], according to which mixed sludge's water composition is 74.6 wt.%.

Already existing industrial drying processes require a lot of space and a large amount of energy to operate. Thus, the absence of external sources of energy such as electricity, renders the task of designing a dryer for the specific, self-sustained system particularly challenging. Another constraint is set by the limited space available, as the toilet needs to be home-scaled. Moreover, the dried matter resulting from the dryer needs to be consistent, while the drying cycle needs to be completed within a reasonable period of time to maintain the combustor's operation. Despite these challenges, drying faecal matter deriving from a single, home-scaled toilet does not involve many of the typical difficulties faced by general waste treatment processes, namely the diversity of origins and the heterogeneity of physical, chemical and biological properties [5].

Although there is a vast literature on sewage sludge treatment, very limited research has been conducted on the technological aspects of dewatering and drying human excreta, particularly at a household-scale. Therefore, any research to this direction is of significant value to researchers who work on water and sanitation projects, especially for the developing world. Given the energy content of human excreta (~25 MJ/kg), which is higher than the one of wood biomass [6] and the health benefits resulting from avoiding open defecation, it becomes apparent that there is a high value in developing a technology for home-scaled faecal sludge drying. The performance and energy balance of the developing waterless toilet rely heavily on the efficiency of the dewatering and drying processes, as they probably constitute the most energy-consuming activities within the system.

II. DESIGN METHODOLOGY

The project execution consisted of seven main stages. The first four stages concern the conceptual design of the dryer and are as follows: objectives identification, literature research and experimentation, evaluation of alternatives followed by concept generation and rapid prototyping. At the end of these steps a Proof-of-Concept prototype was obtained, since the prototyped concept passed the initial tests and seemed to work in principle. The second group of activities, namely stages 5 to 7, aimed at further developing the designed concept based upon the insights gained from the previous stages. The last three stages are design refinement, advanced prototyping and testing. Figure 2 depicts the dryer's design methodology along with the corresponding Technology Readiness Levels (TRLs), as defined by NASA [7].

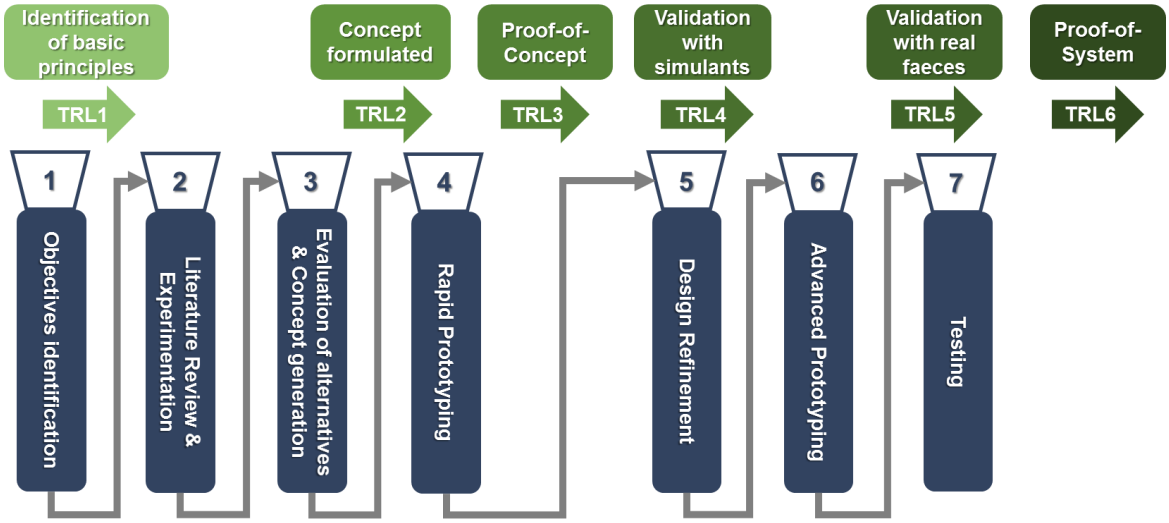


Fig-36: The dryer design methodology

III. DESIGN AND DEVELOPMENT

The challenging task of drying faecal sludge was broken down into three main functions: mechanical dewatering to bring the moisture content down to 60 wt. %, thermal drying to reach 20 wt. % and finally, formation of pellets weighting 1-1.5g each. The function analysis of the dryer is shown in Figure 3.

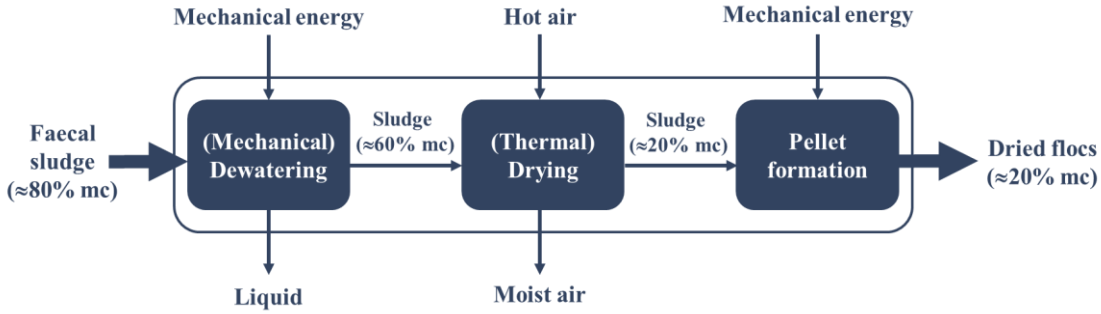


Fig- 37: Dryer's function analysis

A rapid prototyping approach was adopted early on the project based on a 'fail fast, learn fast' logic. The goal was to gather practical insights, which would then lead to the rejection of concepts that do not work and to identify problems and potential solutions. This is why very basic and low-cost materials were used for the rapid prototyping stage of the design process. Such materials include tin cans, wood, plastic, Meccano parts, screws, nuts and bolts.

Early findings from literature review and experimentation suggested that conduction would work in favour of the bottom layer of sludge, while convective heat would efficiently remove moisture from the top layers. Thus, if the thickness of the sludge cakes was small enough, heat would penetrate from both sides and therefore, the idea of using a metallic drum with a scraper to create a continuous, but simplistic, conveyor type system came up (Figure 4a). In order to compress the sludge and provide dewatering, the concept was soon converted into a two-drum design (Figure 4b). This way, the 'stickiness' of faecal sludge would be used for the dryer's benefit, as it would enable the system to dry the sludge which was stuck on the drums, using the heat coming from the bottom of the chamber. Then, the dried flocs would be scraped off, whilst the water produced during the dewatering and drying stages would be gathered using a channel placed at a lower level and in between the rollers. An important observation concerned the position of the scrapers. Whereas in the initial design the scrapers were positioned below the drums, it was found that if they were moved to the top, this would create a much larger drying surface. Finally, a cover would increase the efficiency of the system, as it would be capable of retaining heat (Figure 4c). The idea behind this conceptual idea was to exploit the heat generated by the combustor (i.e. coming from inside the system). This would comply with the project's requirements for an energy-neutral system. Despite the obvious benefits from a system's perspective, the reliance and interaction between the dryer and the combustor would make the whole effort even more challenging. All the parameters regarding the air entering the dryer (e.g. temperature, moisture content, flow rate, pressure, etc.).

Fig- 4: From left to right: **a)** Single drum concept, **b)** Double-drum concept, **c)** Low-fidelity prototype

At this stage, a series of tests were performed to get an indication of whether the prototype was a move to the right direction or not. The tests showed that the desired moisture content could be achieved within half an hour of drying, at a temperature higher than 105°C. Thus, the concept was considered as proven and the green light for further development was given.

The drying system concept had then to be refined by incorporating the learnings form the testing phase. Furthermore, the next version should entail a more integrated design, suitable for testing in a harsher environment and capable of satisfying requirements, such as cost, manufacturability, robustness and easiness to assemble and to operate. The analysis of the aforementioned parameters and the CAD design of

potential solutions lasted for about five weeks. A few examples of examined designs are illustrated in Figure 5.

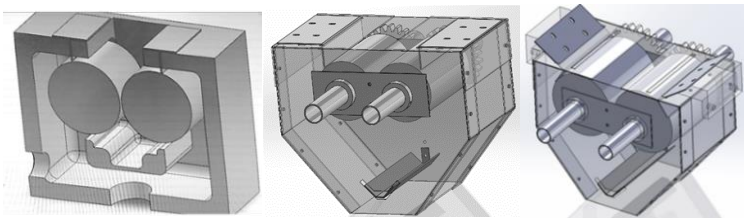


Fig- 5: Examples of CAD designs for the dryer

For the surrounding cover used to retain the heat, the concept of a thin stainless steel frame was selected. Stainless steel was chosen as it constitutes a tough, heat conductive and corrosion resistant material with high temperature strength properties. A circular frame such as the one used for the proof-of-concept prototype could not be used, as the cost of steel casting would be extremely high. Except for being effective and efficient, the dryer had to be easily manufactured at a realistic cost. Hence, an assembly of stainless steel sheets that could be cut and folded was preferred from a circular enclosure (Figure 6, second row). Another feature of the selected design was that it could accommodate two drum sizes, which could be fitted into the dryer. Finally, the distance between the drums was adjustable between 1.5mm and 4mm. These design characteristics would allow various options to be tested on the same prototype. This in turn, led to a minimal prototyping cost and enabled the independent variables concerning the interior of the dryer to be constant for all the tests that would follow.

Figure 6 illustrates all the different variations of the dryer prototypes from the early development stage until its current phase, which corresponds to a TRL 6. An important note that has to be highlighted, is that the design refinement process was a long-lasting one, and that all the prototyped versions relied on practical insights obtained from making, assembling and testing each prototype. These practical insights were crucial and played a decisive role in finalising each design and fixing the problems that occurred throughout the process.

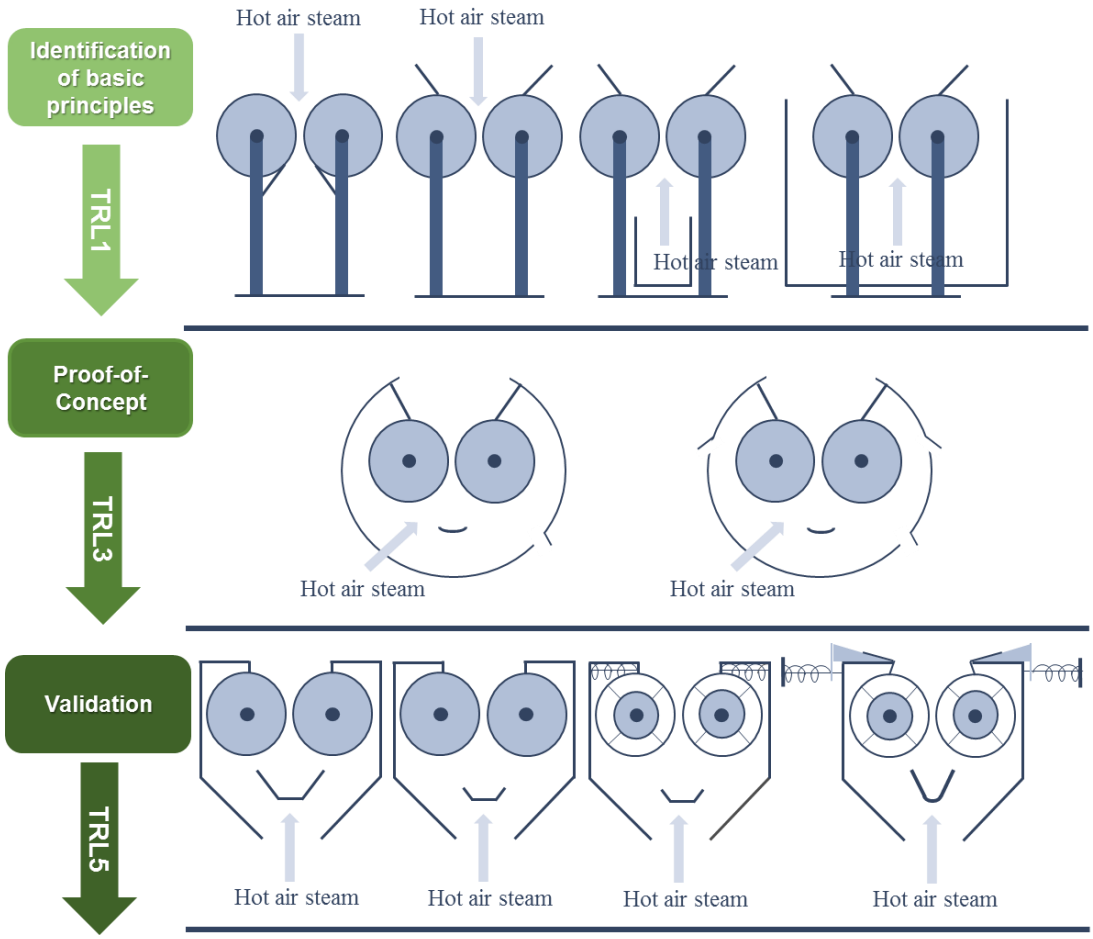


Fig- 6: The evolution of the prototypes throughout the design process

IV. PERFORMANCE EVALUATION

The latest prototype constitutes an integration of all the sub-concepts designed and modified throughout the development journey. It was also ensured that the robustness of the prototype would be sufficient for the testing procedures. The testing rig that was used to prove the concept consisted of:

- A Eurotherm 2216e PID temperature controller.
- An air compressor, with an approximate flow of 3Lpm and a 5.5 mm outlet pipe.
- An AHP-7562 Omega Air Heater.
- A K-type probe, 480˚C rated, 1m lead.
- A pipe 152.4 mm long.
- The dryer.

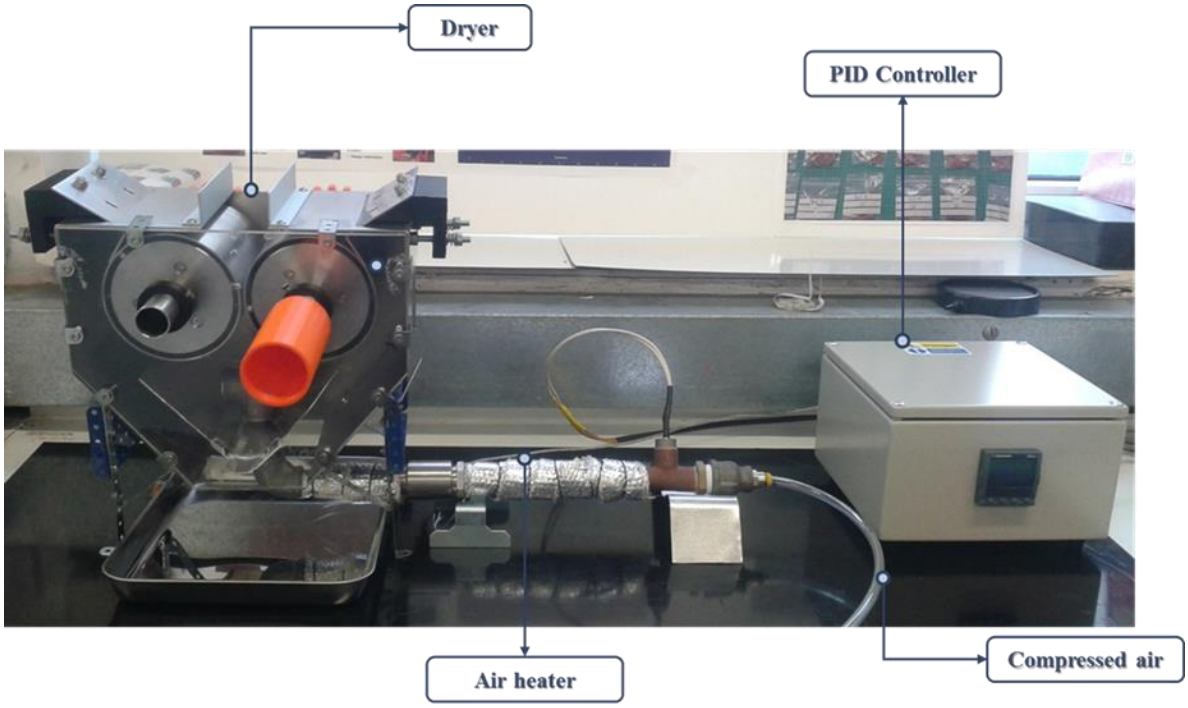
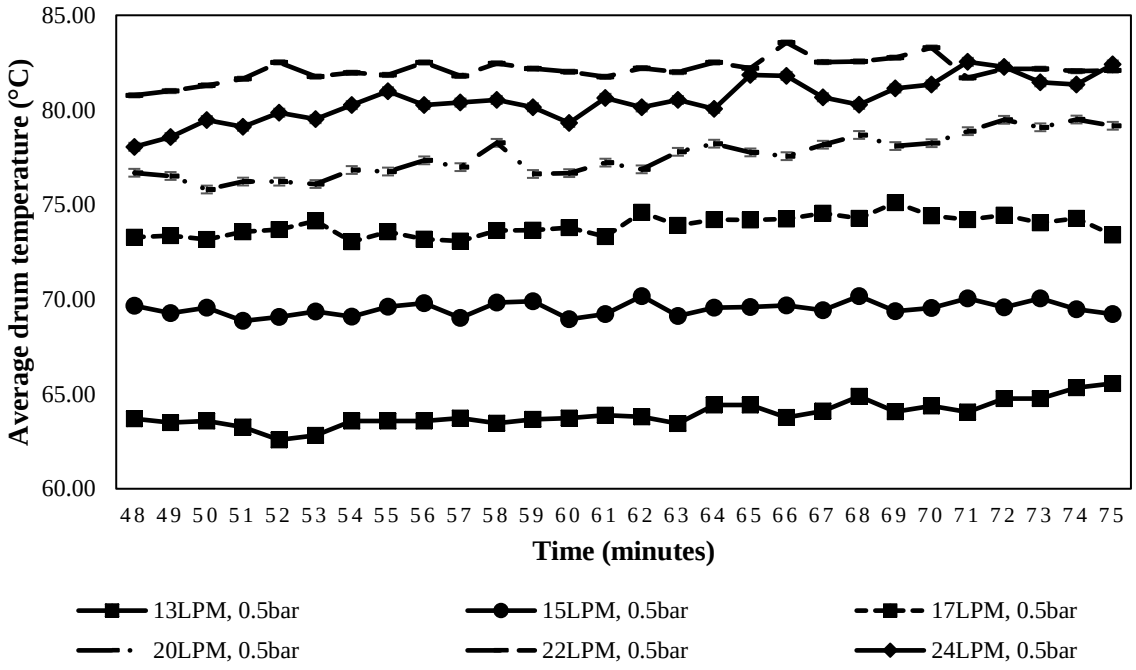


Fig-7: Experimental set-up

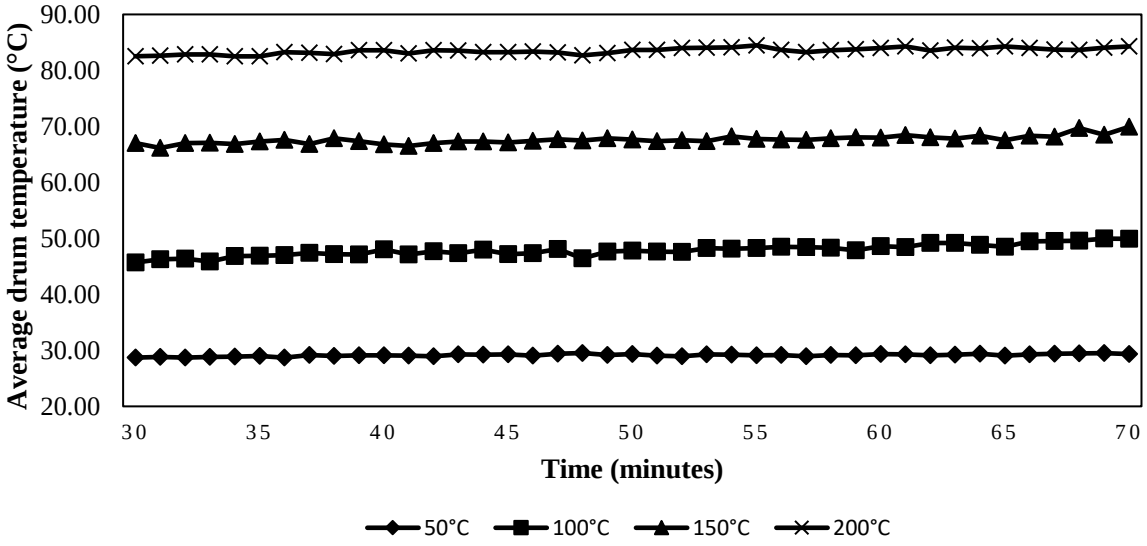
The first part of the testing process focused on the identification of the optimal air flow rate that should be provided at the inlet point of the dryer. After considering the boundary conditions as defined by calculations concerning the system air and energy flow, it was decided that the inlet air flow rate could not exceed 24lpm (litres per minutes). Thus, an experimentation phase began, testing various flow rates and recording the corresponding temperatures at 5 different points inside the dryer. The average drum temperature for flow rates between 13 and 24lpm is shown in Graph 1. The air was provided via a compressed air line. The air pressure for the following graph was 0.5bar and the air temperature was ambient.



Graph-1: Average drum temperature per air flow rate

Although according to theory, the higher the air flow, the higher the mass flow rate, the results showed that there was not a significant difference in terms of drum temperature between 22lpm and 24lpm, probably due to turbulence or other thermodynamics phenomena inside the system. It was therefore decided to select 22lpm as nominal air flow for the dryer inlet.

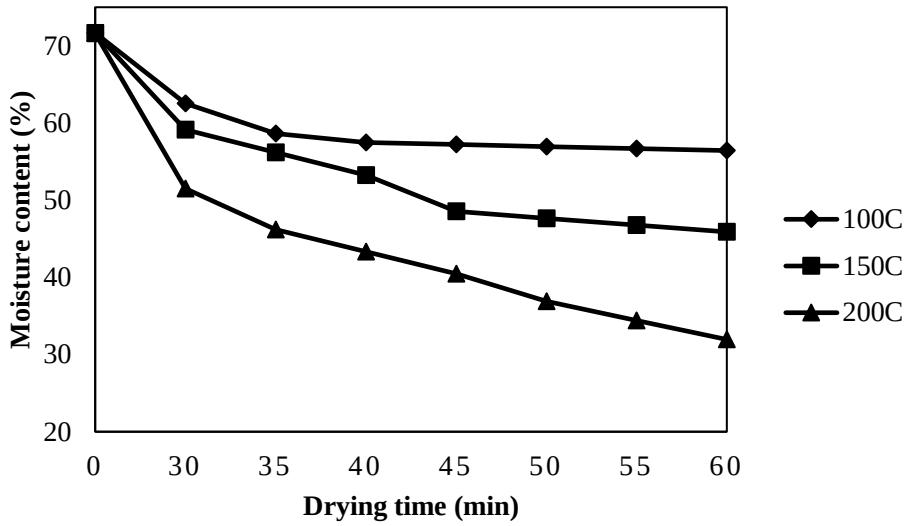
As a next step, and based on the selected air flow rate, the minimal required temperature for the dryer to operate had to be defined. Based on calculations related to the minimal, average and maximum air temperature that could be retrieved by the combustor's exhaust outlet, a temperature of 200°C was considered as a fair temperature for the dryer, but also a possibly achievable one for the combustor. For a fixed air flow rate of 22lpm and varying inlet air temperature, the average drum temperature was recorded as shown in Graph 2:



Graph-2: Average drum temperature per inlet air temperature

As expected, the results confirmed that the losses in the tested, early-stage prototype are quite significant, as it is not sealed and insulated properly.

The latest series of drying tests were performed using simulant of faeces ('synthetic sludge'). The simulant selected consisted of miso, water and psyllium, as it was found that its density and stickiness properties were closer to the ones of real faeces. The moisture content of the sludge was measured 70 wt. %. The dependent variable examined was the moisture content of the sludge after certain periods of drying time. The qualitative variables observed were the functionality of the key parts of the prototype (drums, scrapers, liquids channel). The tests were performed with ambient air moisture content, the inlet volumetric flow rate was 22lpm, the pressure 0.5bar and the temperature at the entry point of the dryer was 200°C. The dried samples were collected at 5-minute intervals. Following the drying process, the samples were placed in the oven for 24 hours at 105°C. Their weight was measured before and after the drying process, using a high-accuracy scale to calculate their final moisture content. The results are presented in Graph 3 and Figure 8 shows pictures of the sludge samples per drying time.



Graph-3: Moisture content of simulant sludge per drying time (22lpm, 200°C inlet air)

Fig-8: From left to right: samples of simulant sludge after **a)** 0, **b)** 30, **c)** 35, **d)** 40, **e)** 45, **f)** 50, **g)** 55, **h)** 60 minutes of drying

Based on the data gathered up to date, the dryer can achieve a moisture content of 30 wt. % within 60 minutes of drying at a flow rate of 22lpm and an inlet temperature of 200°C. These results are close to the desired ones (20 wt. %) and it is hoped that the implementation of certain design improvements, the heat losses will be reduced significantly and the dryer's efficiency will be improved drastically. The ultimate goal is to achieve 20 wt. % within almost 30 minutes of drying time; a benchmark that has been achieved with the current design (both with simulant and faecal sludge), but at a higher air flow rate.

V. CONCLUSION AND NEXT STEPS

This paper reviews the design and development of a drying device, which is part of Cranfield University's self-sustained and waterless toilet. Its purpose is not to enclose all the details already considered or the ones that have been derived to date, but to present in a concise way the design process of this novel technology up to its current readiness level.

There are several limitations regarding the developed technology needed to be acknowledged. An important limitation is related to the complex testing procedures required. Many testing rigs are still in the development phase, as they require very precise equipment to acquire measurement data. In fact, often each test involves different procedures and equipment, depending on the dependent and independent variables examined each time.

There are still challenges to be resolved. A key one concerns the energisation of the moving parts of the dryer. As the scope of a powerless toilet is restrictive in terms of the use of external power sources, a system to drive the moving parts is being designed. An additional procedure is also needed to convert the dried flocs into combustible masses of around 1g each. A technology suitable to serve this purpose has been designed and is about to be prototyped in the near future. Both additional technologies will be positioned around the dryer, in a way that the system's restrictions in terms of space are satisfied.

Finally, design modifications that are about to be implemented to increase the efficiency of the drying process have been identified and are being implemented.

VI. ACKNOWLEDGEMENTS

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