Delft University of Technology

What Leonardo could mean to us now
Systematic variation 21st century style, applied to large-scale societal issues

Kersten, Wouter

DOI
10.4233/uuid:2b5626ca-1a12-44e9-88da-6d898b06b751

Publication date
2020

Document Version
Final published version

Citation (APA)
Kersten, W. (2020). *What Leonardo could mean to us now: Systematic variation 21st century style, applied to large-scale societal issues*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:2b5626ca-1a12-44e9-88da-6d898b06b751

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

WHAT LEONARDO COULD MEAN TO US NOW

Systematic variation 21st century style applied to large-scale societal issues

Wouter Carel Kersten

What Leonardo could mean to us now

Systematic variation 21st century style
applied to large-scale societal issues

Dissertation
for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Tuesday 17 March 2020 at 15.00 o'clock

by

Wouter Carel KERSTEN
Master of Science in Environmental Science,
University of Greenwich, United Kingdom
Master of Science in Industrial Engineering and Management,
University of Twente, the Netherlands
Born in Den Haag, the Netherlands

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus,	chairperson
Prof. dr. ir. J.M.L. van Engelen	Delft University of Technology, promotor
Dr. ir. J.C. Diehl	Delft University of Technology, promotor

Independent members:

Prof. mr. dr. ir. S.G. Santema	Delft University of Technology
Prof. Dr. P.V. Kandachar	Delft University of Technology
Prof. dr. R.T.J.A. Leenders	Tilburg University
Prof. dr. A. Montuori	California Institute of Integral Studies, USA
Dr. ir. G.S. Celik	Aalto University, Finland
Prof. dr. A.R. Balkenende	Delft University of Technology, reserve member

Cite as:
Kersten, W.C. 2020. What Leonardo could mean to us now. Systematic variation 21st century style, applied to large-scale societal issues. Doctoral thesis, Delft University of Technology, Delft, The Netherlands

ISBN: 978-94-6366-260-4

Cover by Astrid ten Bosch, MSc
Lay-out by Jairo da Costa Junior, PhD

Printed by: Gildeprint

Copyright © 2020 by Wouter C. Kersten
All rights reserved. No part of this publication may be reproduced, stored or transmitted in any form or by any means without written permission from the author.

Paraphrasing a well-known expression: it takes a village to produce a PhD thesis. This manuscript is the evidence that 'my' village has succeeded. At this moment in time and place I would like to dedicate this result, possibly to their surprise, to my mother and sister. Both have met with adversity that I have not experienced to that extent. More importantly, they bounced back to greater heights than ever before, and that has turned out to be an undeniable source of inspiration for me.

PAGE INTENTIONALLY LEFT BLANK

Table of Contents

Summary

Summary

Current situation

Design engineers have an inherent drive to create something novel, usually a product. They also prefer having the freedom to let their creativity flourish to do so. However, they also need to create something that is relevant to society and their principal, at least when they aim to address an actually experienced problem. Since WWI the rise of industrialisation-driven systematic design helps to create better, relevant results. Creative freedom is thereby structured to some extent to increase the chance of this relevance occurring.

The standard design engineering process consists of discursive steps and constant verification of the list of requirements with the results from each step, which can result in a modification of the requirements. All steps contribute to fostering the creativity that is used to benefit the (societal) relevance and a satisfactory design outcome.

This structure within which creativity operates can be clarified further by highlighting the main characteristics of a design engineering process: the design task is derived from the problem definition and scopes the challenge for the designer. After the design task has been set, systematic variation can first be applied to decompose the task/problem, and later on to create the morphological chart (developing partial solutions) and to try out different combinations to arrive at a set of possible integrated solutions. During this process the result of each step is checked with the list of requirements stemming from the design task which can result in modification of the requirements. Steps do not follow a fixed sequence (discursiveness) and requirements can evolve throughout the process. When recomposing the set of integrated solutions, when matching these with the requirements and when selecting the final best choice, satisficing is used. The choice for the final solution is the optimal one in relation to the scope as defined in the design task. How it might conform with requirements beyond that scope is not of primary interest.

The problem

Design challenges are becoming increasingly complex, amongst others because real life is getting more complex: society is more interconnected than before and most problems occur in a variety of -quickly changing- shapes and forms, i.e. in different contexts, that often have interdependencies as well. Additionally, design challenges in real life are not isolated, they interact with factors that designers cannot actively influence, including (geo) politics, structural inequalities and even specific ad hoc crises All this can for example be seen in all problems related to sustainability. From the design engineering perspective, the different contexts result in a diversity of requirements. How can design engineers, within the limitations but also capabilities of their profession, respond to this rise in diversity and the likely interdependency between different contexts?

Being allowed to be creative is ‘non-negotiable’ for most designers. The answer is therefore often sought in the structuring aspect. To reduce the complexity and increased diversity the common response is simplification, e.g. choosing one context as scope of the design task. Context can here be considered to be a set of circumstances that belongs together in which a specific manifestation of a more general problem is experienced. Common examples of possible contexts are countries or regions, or specific target groups within these. Within the simplified design task the designer attempts to unleash creativity to arrive at an optimal solution for the chosen scope.

What can be seen in practice is that this way of working in a highly globalised, interconnected and fast-evolving society with ditto problems no longer suffices. The initially optimal solution sets the path for next steps in the implementation process, i.e. it creates a path dependency and lock-in for implementations beyond the initial context. The efforts that are then required to redesign solutions to match other sets of contextual requirements limits, slows down or even blocks the path towards positive large-scale impact. Especially if the problems refer to sustainability and basic quality-of-life issues, the scale is indeed large, interconnections are abundant and the need for impact is high. Several projects during the first decade of this century, including ones at this faculty, brought this problem to light already; but have so far not resulted in major changes in common practice.

Research focus

It is therefore worthwhile to investigate what (types of) changes might be called for in design engineering to respond more effectively to this development. As mentioned before, design engineering alone, cannot address all aspects of achieving positive impact on a large scale. Further evolution of design engineering might however provide a relevant *contribution*. The change, i.e., next step in this evolution, that is the topic of investigation in this thesis at the same time needs to provide a new perspective but should not be too alien to design engineers. For that reason the most common overall design engineering process is used as main benchmark.

A good choice for the core of the change that represents “new perspective but not too alien to design engineers” seems to be to use the oldest design characteristic as a basis: systematic variation. This was pioneered by Leonardo da Vinci. The change is to not wait to use this characteristic until the design task has been defined, but to also apply it before that point in the process by considering multiple contexts early on.

The Main Research Question (MRQ) for this thesis has therefore been formulated as follows:

Which theoretically and empirically supported insights and knowledge can be generated with regards to a design engineering approach that uses systematic variation of contexts before the design task has been set, in order to address, in particular, multi-contextual complex issues in society?

To provide further focus and clarify the emphasis for this research, two main angles are introduced. These angles will guide the scoping of the literature research, and help to structure the findings, discussion, conclusions and recommended next steps.

1. **Design engineering arsenal**: based on our knowledge of the current arsenal of (systemic) design methods and tools, what can an approach with the focus as expressed in the MRQ add? To appreciate the question, it can be expected that some main defined constructs deserve closer inspection. The choice for these constructs is based on exploratory research, they are investigated in depth later.
    - Contexts: in this research a **context** refers to a set of circumstances that belongs together in which a specific manifestation of a more general problem is experienced. What distinguishes one context from another? An obvious and common distinction is to use country borders as main delineator but depending on the issue other types of distinctions may however also be relevant. At the same time, considering too many contexts may stifle the process. How to identify and select relevant contexts?
    - Richness of the design space: when applying this multi-contextual reality to setting the design task, the scope of that design task is broader than currently is common, with intent. This broadness may seem daunting because it leads to an increase in information that the designer has to deal with. It is therefore important to bear in mind that the intentional diversity of this information feeds the design space with a **rich** volume of information, that is likely to capture the interconnections and interdependencies between the different contexts. To appreciate this, this notion of richness needs to be better understood.
    - Adaptive product/ service architectures: a contextually optimised solution falls short of meeting requirements in a multi-contextual reality. The desirable *design* outcome would rather need to be an **adaptive architecture that is robust towards different end-use scenarios (contexts).** This implies that with at most minor variations the architecture can serve requirements in different contexts.

2. **Empirical framing**: in the faculty and section where this research is hosted, the types of issues addressed concern sustainability (impact) on a large scale and inclusiveness, which often both imply complexity. These are the issues that this research focuses on. One feasible adjacent field to take into consideration to encourage that a change in design engineering practices can contribute to achieving large-scale impact is 'management'. This thesis will therefore explore how changes in product/ service development could be aligned with management considerations and decision making to ensure a longer term view (implementation in multiple contexts).. Furthermore, because of the focus of the empirical part of the research (see Research approach), the implications for design engineering education are to be investigated as well.

Research approach

This thesis represents exploratory research so the research approach, described in detail in chapter 2, needed to be inductive. The scope as described earlier is still broad. To make the research more concrete, a design engineering approach was proposed to take centre stage to create a recognisable anchor point in the research. This approach revolves around the main constructs as outlined above: 1) **systematic contextual variation** *before* the definite design task is set, 2) resulting in enhanced **richness** in the design space, 3) enabling the designer to create a well-informed *inherently* **adaptive architecture** *as design outcome*, 4) which will increase the ability to achieve **sustainability impact on a large scale**. The design engineering approach that is proposed to take centre stage is called Context Variation by Design (CVD), i.e. intentionally varying the contexts to match the complexity of the design challenge. Using this approach as core one in this thesis does not suggest that it is the only or best 'method' to address the problem as stated.

The themes for extensive literature research (chapter 3) were derived from the two main angles and are: *design engineering history*, *a globalised society*, *achieving large-scale sustainable impact* and *dealing with complexity*. Following the inductive process, the results of this extensive literature research were – in iterative fashion after extensive debate with design experts - condensed into a set of **theoretically backed propositions.** These propositions are *not intended to be tested or falsified* because they are not hypotheses. To formulate hypotheses there would need to be an expected and extensively substantiated relationship between two or more theories. This is not the case here. This thesis attempts to address the stated problem. It does so by developing more informed insights. The propositions are however intended to be elaborated upon by means of empirical cases. This results in an empirically supported appreciation of their level of plausibility, which is then input to suggest next steps for elaboration of this line of research and for practitioners. The real-life situations that were available for this research to select the cases from, except for one, involved MSc-level students, mostly in Industrial Design Engineering (IDE). These are design-engineering-professionals-to-be with a good base level of design knowledge *and* openness to consider to enhance their arsenal of design approaches, methods and tools. At the start of the thesis-trajectory, expert designers in companies had been approached for their direct participation. Their responses demonstrated reluctance to try out a way of working that they were not familiar with and they suggested to first try out the approach a bit more. Working with advanced students therefore was the best option. In the one exception real-life situation the researcher had direct access to the external professionals who were in charge of that specific situation and were willing to discuss retrospectively how another approach than they had taken might have had different results.

From the 23 available real-life situations seven were selected to be used as cases to be included in detail in this thesis (chapter 4). The selection was based on level of access to high-quality and rich information of process and outcomes, relevance for this research (i.e. results covering one or more proposition topics) and as a 'bonus criterion' whether a case had during the thesis-project been included in academically reviewed publications of which the PhD-researcher was (co-)author. The results of the selected cases were captured by the researcher in the form of case-specific findings clustered per proposition while using a diversity of available sources as input and for joint interpretation (design reports, meetings, interaction during conferences and other communication with involved stakeholders, and in-depth discussion with design experts from the faculty). The case-specific findings were subsequently synthesised into overarching *empirical insights per proposition*, 41 in total, and scrutinised in several iterations by design experts and practitioners before they were made final as presented in this thesis. The analysis of these **empirical insights per proposition** was intended to identify specific or overarching **patterns** in relation to the themes that had been captured in the **theoretically-backed propositions.** Thereby it could be assessed how plausible the propositions were as well as how they can be elaborated further. The patterns were expected to shed light on possible contributions to existing theory and to design engineering practice.

Main results

After having analysed the aforementioned patterns emerging from the seven cases, the following main results emerged (chapter 5):

- Propositions were by and large more supported than opposed by the empirical insights (20 vs 4). The number of insights that supported propositions was somewhat higher than insights that indicated the need to *frame proposition-themes differently* (20 over 17). These numbers should not be considered as numerical evidence because they do not capture differences in strength of the insights in relation to the propositions. These results merely provide a first glance how the propositions fared when confronted with the empirical insights. This provides a rough idea about their level of plausibility and directions for further development.

- Design engineering students were able, if so encouraged, to vary the contexts before a design task is set. That variation was mostly limited to geographical distinctions. This implies that while design outcomes in the cases were promising, they might have even been more robust towards different future scenarios if other relevant contextual distinctions would have been considered as well.
- By varying contexts intentionally, the information that was considered within the design task was *voluminous, diverse and relevant*. This reduced the necessity to reach for arbitrary information that was not linked to the design task to make new creative connections. The richness in the design space feeds the architecture boosted creativity (identifying and making new novel connections) as well as the effectiveness (achieving a desired functional result) of the design process. This was explicitly experienced and demonstrated by most of the students in the cases.
- In a few cases the quality of the design outcome of CVD-driven design processes was compared to similar results which were achieved without using CVD. In these instances – i.e., results of three comparable design concepting sessions, performance testing of a gasifier stove and opinions during a cook stove stakeholder summit – signs were explicit that the result with CVD was considered superior to comparable outcomes without CVD. These positive signs cannot be considered to be conclusive evidence but do provide ammunition to support continuation of this line of working.
- When assignments were executed that were short (i.e. days vs months), under time pressure and without much at stake, e.g., one assignment as part of an MSc-course, the appreciation, understanding and actual results were quite diverse across the range of students. Even in these circumstances a reasonable number of students did indicate to appreciate both the intention and the potential of an approach like CVD.
- In most cases in which the students executed full design assignments the students as well as their academic and non-academic supervisors, were generally more appreciative of the potential of CVD. It also became apparent that the process to create the adaptive architecture, as expected, took more time at the start, but this time was often saved later on in the design process because the students had rich information to fall back on to make choices. They did not necessarily take longer to complete the design assignment as a whole, the intensity-distribution during the assignment was just different.

Additionally, with CVD after they had finished their assignment the potential for the scalability of the result was clear, from a design engineering perspective. While both types of results should also be appealing from a management perspective, during the execution of the cases it was generally not easy to let people in management positions fully appreciate these benefits. This may have to do with how these benefits are framed exactly. The same challenge is likely to occur in dialogues with other types of stakeholders.

- Further alignment between the design and management realities is therefore relevant. Both professions have different priorities and dominant framings. The cases and research have provided some clues how the latter might need to evolve to aid this alignment. Similarly, it became apparent that when the design challenge is a multi-contextual one a design team with diverse skills is likely to perform better.

Conclusions

These results feed into a proposed improved version of CVD, 2.0, This upgrade does not change much about the fundamentals of CVD 1.0, but can be considered to represent fine tuning regarding emphasis and framing of certain aspects. The main aspects of this upgrade, clustered following the main angles for this research, are highlighted below.

- **Design engineering arsenal:** a better understanding of the key defined constructs:
  - **Contexts** can be distinguished in different ways that are relevant for the design task. It is advisable to spend more time on investigating the key dimensions of the problem. This can help to choose *design relevant contexts*. By doing this early on, the actual design process will be wide (covering *several* contexts) as well as directed (*relevant* contextual choices are made). This will save effort by not having to source from arbitrary *design task-irrelevant contexts.* Emphasising this explicitly to design engineers is desirable, to discourage only going for obvious ones that insufficiently capture the diversity of the problem.
  - **Richness** in a design space is determined by the volume of information ('resolution') that is inherently relevant ('focus'). Because CVD encourages volume and relevance of information in the design space it increases the potential to arrive at superior design results that inherently reflect (creative) interconnections between these design related contexts. Even a rich design space cannot account for all the non-design related challenges in the process to achieve impact. Nevertheless, in a rich design space it is likely that information surfaces that provides clues about potential large-scale implementation challenges outside the direct design domain.

- To resonate with a broader audience, it might be useful to imagine an **adaptive architecture** as representing a product-family. A way that might effectively capture this communication-wise is to present this architecture as having three 'layers', namely one with generic or "no regret" components, one with adaptive modules and one with context-specific components. This may help to convey the message that the applicable product version for each context will have similarities with versions for other contexts. A configurable platform that would be based on requirements from one context would require assumptions about what needs to be flexible. Creating a fully flexible platform results in over-dimensioning (providing a huge range of options on everything) and basically means not making any choices.

- **Empirical angle, (potential for) large-scale impact, management considerations:**
  - Signs for the superior nature of design outcomes of a CVD-driven process, in the context of large-scale sustainability issues, have materialised in several cases. This refers to the quality as perceived by for example principals, peers or determined by comparative performance testing. Again, this is not yet conclusive evidence, which was also not the primary goal of this inductively oriented thesis. It would require systematic, abundant (i.e. large volumes of comparable observations and data points) and arguably more artificial (i.e. non real-life), set-ups to collect the material for such conclusions.
  - CVD provides a systemic perspective, which requires a strong level of cooperation between professionals with different skills, also within the design team.
  - To create conducive conditions for an approach like CVD, managers would need to combine more longer-term oriented metrics with the more common short-term ones, like initial time-to-market and quarterly sales results. The research could not be extended far enough to explore the acceptance by practitioners of such metrics.
- **Empirical angle, Implications for design engineering education**:
  - The research has demonstrated that CVD is a relevant extension of the arsenal of methods taught in design engineering education. Version 2.0 captures changes in framing and communication that should facilitate effective use of the CVD-approach. There is still a legitimate argument to be made that not all design engineers(-to-be) can or should want to take on roles in which they have to deal with multi-contextual complexity. The range of design roles is large enough for different skills to flourish, from more aesthetic ones via pure product development, to more strategic ones.

- It turns out to be relevant to be aware of the limitation of what design engineering, even with a systemic and multi-contextual mindset, can do. Design is an important component of a larger process to try and achieve a better society, it is not the only one. Design educators might need to find a good balance in conveying the importance of the profession as well as the need for design engineers to be humble enough to realise that they can only improve society together with others.

Next steps

The results give rise to many possible areas for next steps. The following are the main ones presented here. As a general rule these next steps also need to be executed in an inductive manner, as is fitting for design research. The suggested areas for next steps are clustered following the main angles that were used throughout the thesis.

- **Design engineering arsenal:** **“**Revelling in richness”. Further explore the development of richness as defined construct in design spaces and how it can contribute to superior results of the design engineering process.
- **Sustainability-Impact on Scale:** **“**Going for Gold”. Enter into a multi-year commitment to truly investigate the longer-term potential (implementation and impact in multiple contexts) in real-life settings. This might include addressing non-design engineering challenges of the process to achieve large-scale impact.
- **Management alignment:** “C’est le ton qui fait la musique”. Investigate (framing of) notions that resonate with managers to bring their priorities in line with those of design engineers to increase the chances that large-scale sustainability impact actually occurs in practice. Investigating framing of notions that resonate with other stakeholders as well might prove to be a worthwhile extension.
- **Design engineering education:** “Leave no Leonardo behind”. Further explore what type of guidance, supervision and conditions would help to encourage multi-contextual approaches during education. This includes exploration whether openness to such approaches is a sensible indicator for future role that a design engineering student might aspire to.

List of Tables and Figures in Main Text

Tables

Figures

Chapter 1

Chapter 1 – Prelude: The birth of a thesis: how did an experienced entrepreneurial and design minded thinker end up doing a PhD?

Not all PhD-theses are created equally. In this particular case, it may help the reader to know more about how it all started, which was not in a standard way. This introduction is intended specifically to clarify how the doctoral candidate arrived at the point where the PhD-thesis process was started. This was as much a personal as it was an academic journey. Since the academic angle and style of writing is used for the rest of the thesis, for this prelude a somewhat more informal tone of voice is used as well as the I-form. All of this is intentional and after discussion with the supervisory team of this thesis acknowledged as a valuable add-on to the formal academic part. Consistent with the spirit of this idea for a prelude there will not be any references in this prelude. Of course, relevant references that were accessed in this period are included in the later chapters, mainly 2 and 3.

1.1 A Thesis has one author but can have different unexpected parents

The birth of this thesis may in fact have started in the previous decade. It must have been in 2008 or so when I was sharing my experiences with an academic colleague who was pursuing a PhD at that time. I was enthusiastically telling her about my workshops with students on entrepreneurship, creativity and innovation. As far as I could tell, the workshops seemed to resonate and opened some eyes, at least partially.

At the same time I was doing part-time academic work, so I did see first-hand how the stories, examples and vision that I presented were at the same time ‘intuitively’ relevant while not necessarily very scientifically grounded. So at some point I asked my colleague: “Do you think I should perhaps strive to do a PhD?”. I was hesitant in asking the question. My own feelings at the time were roughly: I like what I am doing, diverse, feet in the mud, and doing research for four years on one topic full time, i.e. the standard format for a PhD in the Netherlands, may simply constrain me too much. The answer I got basically was a more positive sounding version of these doubts: “No, don’t go for a PhD, certainly not for now. Not in any way because you *can’t* do it but because you have so much more to offer as inspirator, engine for change to boost students and others. Focus on that for now”. And I agreed, both with the reasoning and the conclusion.

When I started working at Delft University of Technology a few years later, I still did not have the idea that I was mentally closer to wanting to pursue a PhD. At least not a traditional one, i.e. by applying to a published PhD-position and doing research for four years on a topic that had been chosen and initially laid out by others. And on what topic would I want to work anyway?

1.2 The plot thickens, after widening first (looks familiar?)

Thanks to some serendipitous circumstances I could together with my close colleagues start to explore what I was interested in myself. That interest consisted of an emerging and still fuzzy mix of thoughts on topics like large-scale societal issues related to various aspects of sustainability, the way we deal with them, the role of design and (social) entrepreneurship and concepts like reverse innovation.

In particular the latter was a phenomenon that caught much attention at that time, 2013, and had also caught my eye. While it had many appealing aspects, I had a feeling something was missing. Since I was working at a design faculty by then, I had a rich and diverse source of creative thinking to tap into. Sometimes explicitly but at least it was a conducive environment to think a bit differently if so inclined.

Inspired by my two main working environments (social entrepreneurship and design engineering), and fuelled by my own attitude of curiosity, this was one of my main lines of ‘different thought’: reverse innovation proposes to utilise our creative capacity that we are forced to tap into when we are working in heavily constrained situations but with a horizon to look broader than that. In business terms, the conundrum at hand revolved around (Western or local) companies trying to enter emerging economy markets by providing solutions against very different price/quality ratios than in Western countries because the prospective paying customers have much less to spend, apart from having different (flavours) of needs as well. In other words: if you want to develop “solutions” for such segments, it does not help to shave off 10% off the price of what you already have, you need to come up with something that is 10 or 20 or 50 times more affordable *and* fits local needs and wants. As it turned out, when companies were acting on that insight, and used the local circumstances and resources as a basis, the solutions they came up with were also found to be relevant for more developed markets after some tailoring. Oft-quoted examples include the CGI-machine of General Electric and mobile banking: both were innovations that can be fully attributed to be rooted in resource constrained situations experienced locally. That very aspect resulted in innovations that could not have been dreamt up ‘back home’ but were relevant there nevertheless. This “multiple context match” – adequate functionality against *much* lower costs even for the situation for which it was not intended - at first occurred unintentionally but was realised later on. Seemingly this was a fine development: by being forced to work with more constraints, innovations were developed that turn out to be relevant for less constrained contexts as well. Everybody wins.

But of course, being curious, I did not use this observation as end point of my thought process. Something started nagging me. Why was this phenomenon called “reverse”? Doesn’t that imply a natural order of things in which the West innovates and the rest copies or derives from that? Is that really what, for example, history tells us? For me it was a rhetorical question. Just look at the historical examples of “China”, “Central America” and “The Arabic world”, and it is clear that history slaps us hard in the face when we would claim all innovation comes from the West. It was a first clue that there might be another perspective possible than simply following this new trend, or at least how it was framed. In the meantime, not hindered by too much academic restrictions I wrote a blog post about these considerations, asking these very same questions and suggesting the perhaps more appropriate title “Sunny side up innovation”, smiley face and all. Main point being: it’s fine to see ‘the South’ as source for innovation impetus, but why imply that this is against the natural order of things? It’s just a word, but framing does matter and often reflects an underlying attitude.

At the same time, in the design environment that I was by then immersed in, another phenomenon could be seen, especially in the area of designing products for emerging markets. This was one of the main application areas of one of my – eventual- promotors, and this serious real-life aspect immediately gave a boost to my motivation. That motivation was boosted in particular because the phenomenon, that I will reveal below, occurred for many basic quality-of-life issues: sanitation, drinking water, energy access, food systems, clean cooking and so on. In many of these projects, well-intended designers had worked for many years on even more well intended assignments for an affordable, human-centred, practice-based and user-involved and user-tested product X for issue Y. In short, all the requirements of the de facto standard of Human-centred Design Thinking were followed, and applied to a dedicated use case, e.g. village such and such in country A, or region so and so in country A+1.

In isolation, each of these projects demonstrated wonderful, sometimes even really imaginative outcomes. So what was the problem? Upon contemplating this question and after several discussions, fuelled by the similar debate on the reverse innovation paradigm, the tentative uncomfortable but informed conclusion was this: while the human and user-centred focus for these assignments had very good elements in it and definitely seemed more appropriate than a range of technology-push projects that we also saw occurring in abundance, might one drawback perhaps be that the alternative forced the designers to focus *too* much, or rather too early? Formulated differently, the results of these projects were – with different degrees of success – well-designed products that were optimised for a particular user-group and in most cases took into account requirements from the broader ecosystem of that specific group. In other words, the scope for considering the total set of circumstances to take into account, here defined as context, was deliberately narrow or focused. With as (unintended) consequence that beyond that particular user-group, i.e., in another set of circumstances where the same problem occurred, the product ('solution') that had been fashioned was (much) less appropriate let alone effective.

Upon some further exploration, it became apparent that this was not an exception. In rare cases had this observation of early multi-contextual awareness been demonstrated. Even in those cases, the consequences for the actual design were still limited. The developed products that hit contextual boundaries like geographical or climate zone borders, when they were supposed to be ready to be sold to a larger audience were not an anomaly. In fact, this 'business' perspective on scaling (selling more products to more people) was the dominant experience, and it was quickly gaining ground. Do a quick dive with your prospective customers and users and quickly feed it into a quick, lean, process to get to a working prototype ("MVP"), test it with first assumed customers, get buy-in from funders or investors and then develop and optimise the validated product further. This approach was contrasted with staying in a lab-setting too long, optimising a technology and then throwing it over the wall without much customer-interaction, No wonder it was found superior, if that is your benchmark. But might there still be other strategies, especially once noticing that these optimised user-centred products did not scale very well beyond their first use-case? Or formulated differently, and not by coincidence: what would happen if the impact would be the main driving force of the scaling-effort, and not the desire to sell more products, 'in the quickest way possible'?

Once looking from this angle it became in fact a bit discomforting to see for how many serious problems the progress of addressing them was slow due to very limited scalability of solutions or, perhaps worse, force-fitting these solutions on new user-groups without making many changes. These are all logical consequences offocusing on numbers of products sold more than what these products are supposed to accomplish. Yes, that strategy did make the initially developed products more eligible for mass-production and therefore economies-of-scale thereby in theory improving affordability. But affordability for products that were increasingly unsuitable for the diverse population they were intended for. A Pyrrhus-victory. And whereas for affluent customers in ditto markets it might be a luxury problem, for the markets that we worked in surely not. The key word in these contexts is (social) impact, not market share. Different success-criteria might need to invoke different (design) practices.

Okay. And now what? There were obviously different dynamics at stake here that were driving this process, including how international aid (and trade!) are organised and which incentives drive them. But international politics and development aid is not my main area of interest, rather a spin out one. So, what then? Write another blog?

1.3 It's more than complicated

Taking stock: 1. key insights for innovation may originate anywhere, yet the dominant innovation paradigms revolve around flow and explicitly or implicitly assume a natural direction of that flow; 2. products that are designed for large-scale issues especially when prevalent in emerging economies often have a limited initial scope (e.g. one target group in a specified country) after which scaling to a more diverse audience becomes a problem, thereby slowing down the process of achieving meaningful impact. The diversity in terms of user-requirements that becomes relevant for scaling was not a consideration because it complicated the first step to quick success; 3. Designers are supposed to be good at creatively solving tensions in their design task.

A hunch started to emerge.

All these observations were 'technically accurate' but something seemed to be missing to tie them together. What might be the red thread in this complicated web of observations? And then it dawned on me. It took a few "feet on the table", yet in-depth, conversations with the colleague who ended up being my first promotor, who had a substantial and long-standing track record into these types of challenges. It therefore did not take long until a prime suspect for the missing ingredient was found: the web we saw was not complicated, it was complex. And these are not the same. I'll get back to that. What was immediately clear as well is that this is more than just academic semantics, but it might take more than a free-of-obligation blog-writing action to get to the bottom of this. We might need to take the academic path. Intermezzo: talking about complexity, how *do* designers deal with it, or how they think they deal with it.

1.4 What is complexity and how are innovators and designers addressing it?

So, what is complexity then? And why exactly is it different than complicated? And what does it matter? The questions were easier to ask than it was to produce a solid, non-evasive answer. At least back in those days… But the team that I was now an appreciative part of could not be deterred that easily. If this difference matters, it was exactly the path of academic, or at least curious, exploration that was starting to become appealing to gain insights that would help to capture this difference. Why academic? We noticed that when we carefully mentioned this distinction between complicated and complex in a practitioner-environment we were just short from being bombarded with tomatoes. Their problem in life, but our and my problem at that point in time. So, back to the academic debate for now.

A challenge is complicated when the sheer size of it feels overwhelming. It does however have an internal logic. Once you find that logic, a complicated problem can be attacked with resources. It is a matter of putting these to work and then the actual problem can be solved. A famous quintessential, albeit still extraordinary example is the Apollo project culminating in the moon landing. Of course, at first it was more than complicated, the team had not yet reached the point of tackling the internal logic of the challenge. It is conceivable that with fewer resources, less patience, less stamina from the many (anonymous) team members and less vision and commitment from 'the top', the logic would not have been found in time and the problems would have remained unresolved.

Complexity however is a different beast. A challenge, and by extension a design task, is complex when, in simplified (but not simplistic) terms: 1) there are many elements to consider that are connected in obvious and less obvious ways, 2) the boundaries of the system under consideration are also likely to be non-evident, 3) because of the many interconnections, it is far from clear what happens if you focus on a particular part of the system ("problem"), 4) even more frustratingly, if you think you have found a solution and try it out again, the results might be completely different. In other words, you might be able to understand small parts but the collective behaviour remains a mystery, 5. And to top it up, the reverse is also possible, that you roughly grasp the behaviour of the system as a whole, but have little clue about what is going on in the different parts. Whether all this is a problem in real life depends on how you deal with it and especially on whether you are focused on "solving" a problem, as so many people are convinced they have to do. To solve a problem that seems too much to handle at one time, the intuitive response is to narrow the scope of where and how it occurs, focus on one type of occurrence (manifestation) of the problem and look at the bigger picture later, once you have mastered the smaller picture. Sounds reasonable and pragmatic, and action-oriented. And everyone recognises how appealing that is.

While I had observed the phenomenon, but not used these exact words until then, I realised that "sustainability", my previous working domain, is also much more a complex than a complicated domain. Sustainability issues are not about distinct points but about whole chains and networks. And it's multi-dimensional, People, Planet, Profit, Prosperity, the whole lot. It's not just about balancing economic and environmental concerns, but the social considerations matter as well, in conjunction. Or to put it into terms that the current Sustainable Development Goals have embraced: development needs to be inclusive, i.e., “for all”. All of these characteristics are signs that it’s not sufficient to just attack one part of the problem, because everything is connected. But “everything” is too much to handle, and can also feel disempowering, so it is certainly appealing to consider the “next best thing”, i.e. to focus on a small part, and hope that improving that part pushes the entire system in the right direction. It’s a bit guesswork, but better than nothing, right? You feel there is some uneasiness associated with this line of reasoning, but it also seems human, understandable, realistic. Still, that nagging feeling…

Why is all of this relevant? Let’s take the, relevant but arbitrary, example of a clean cook stove for end-users in country X. It’s not a hypothetical example, it was one of the main inspirations from practice for the whole thought process and discussion that I am at length describing in this prelude. So it must have left an impression, you might say. Ok, so you are a designer and as taught you use a human-centred approach and throw in lean customer development for good measure, you involve end-users in the entire process, you comply well with the articulated *and* observed requirements of this user-group. Your prototype is just a minimal-effort version when it is validated with representatives of the group of chosen end-users and seems to be satisfactory for all stakeholders that you included. Everyone involved is happy. All lights are green to go-to-market, achieve the success that you will obviously have and then scale. Scaling does sound very appealing and necessary from an impact point of view because there are around 2 billion people worldwide suffering from the bad effects of “dirty cooking”, directly (smoke, health, costs) and indirectly (deforestation). Now there is what you call both a market and a “large scale societal issue”.

.As it turns out after tracking a multitude of these cases from across the planet, there is a clear pattern of what happens in reality. The first step is not the main problem. Sure, the scale is still limited so the costs of production limit the possibilities of bringing an affordable product to these problem-stricken people. No worries, donors can help out, whether you’re a multinational or start-up, because you’re working on an important societal issue. The fact that this does not really prove whether your product is adopted or just tolerated is of minor importance right now. But then the next step: scaling. Selling your beautiful stove to a larger audience, increasing production, achieving economies-of-scale and moving to a full commercial model. You have heard stories about the diversity of dishes, cooking habits, available fuel types and what not in other villages and regions, let alone countries, but how big can these differences be? People will be happy to get a better cook stove anyway, they don’t have time to complain about quality. Or so you believe.

I’ll speed up.

This is what was happening in real life. For cleaner cook stoves and many other products. The chosen path becomes the benchmark, and divergence from that benchmark becomes undesirable because of the investments in that path and the proof-of-concept as all-decisive starting point of that path. Not just in less advanced economies, but also in many Western countries. There was a notable difference however: if people can afford more you can give them more, including much that they do not want or need. Feature overkill. Smartphones with dozens of useless pre-installed apps, software with features 80% of which are never ever used, batteries that need to be recharged daily but so what? Customers pay for it, and many of them can, and you don't have to worry about catering for diversity too much, just include it all including unnecessary features. But in the circumstances that govern basic quality-of-life related products in resource-constrained areas with customers that have low affluence, the dynamics are different. So if this is the demonstrable reality, are we missing something, somehow, despite best intentions being abundant?

1.5 A complex design task

Once you start to read about design engineering and complexity you'll find many writings with optimistic statements how designers more than virtually any other types of professional, are able to deal with complexity. They are imaginative, are not tied to structures, can see and make connections. And yet, humanity still observes the problem we just described. That doesn't seem right.

The search had begun. The search for the nitty gritty of complexity, the way how design (engineering) as a discipline and designers themselves had been dealing with it, the way of framing contemporary challenges, even small experiments with (junior) designers. A tentative breakthrough epiphany was looming. Yes, complexity was a known phenomenon in the design engineering domain. It had been written about and analysed, and reflected upon. Methods had been developed and of course design thinking, or more generally "thinking like a designer" had become synonymous in some circles with "Being able to solve all problems". Almost without realising it I then used a habit which I had developed by being immersed in innovation and creative thinking processes for a decade and which I had labelled as "breathing": looking closer, zooming in on what was being said, then zooming out to get the bigger picture (overview(, and then zooming in again with knowledge of that bigger picture (insight). Not exactly a new Theory of Relativity, but simply calling it Breathing helped me to see new connections, even patterns.

At that time together with my colleagues, I framed these patterns in relatively informal, not yet academically validated terms but it was clear that an interesting path for deeper investigation was emerging. These patterns explicitly reflected the combination of theoretical considerations and applied real-life settings; these are not isolated or contradictory but let's leave that aside for now.

1. Complexity has to do with connections, connections create uncertainty (= a less than 100% chance of X happening) and unpredictability (unclarity whether X or Y will happen, and why), and no one really likes either of these. The option to create a solution which in your mind represents certainty (a 100% chance of X happening) is appealing to the vast majority of human beings, including designers. Leaving aside how realistic this is.
2. Design engineers are relatively well equipped to make new combinations, make creative connections to arrive at novel solutions, once the design task is scoped.
3. Whereas design engineers have some tolerance for tensions and challenges, the average manager is incentivised by reporting progress (does reality follow our plan?) and by monitoring the match with stated requirements (does it look like we said it should look): anything that jeopardises a clear control on budget and outputs is highly suspicious and in principle undesirable.
4. Very few products follow a linear path after their market introduction. Consumers find new forms of use, intended or not, and promising initial successes are confronted with lukewarm reception elsewhere. In other words: successful first steps may say little about success of the next steps.
5. Based on experiences with social start-ups, the requirement of scalability to achieve more impact on society came as a natural area of interest to me. But scalability can be much more intricate than selling a certain product to more customers especially if these customers are more diverse than you initially realised.

The overarching pattern: design engineers experience complexity in their work and may be able to bear it, but there seem to be dynamics at play that do not enable them to make good *use* of that complexity. And as stated before whereas for 'advanced economy' products the problem could in many cases be circumvented by for example feature overkill, for emerging market issues this strategy is not an appropriate option, as many projects had demonstrated.

I had found a continuation of my academic purpose. The idea for a possible topic for a PhD-thesis had reached an embryonic state, meaning it was far from being sufficiently developed, but had started to become an actual option.

1.6 Could the answer be: embrace complexity?

So, where had we arrived, with the calendar showing “2015” at that point in time?

Different ingredients were present, different insights were emerging not least because of my direct connections with different domains: a knowledge-connection with sustainability, a work-connection with social entrepreneurship, an ever-evolving personal connection with applied creativity, a quickly emerging connection with “design (engineering)”, and in general a diversity of interests. A total lack of focus. The worst possible starting point to board a PhD-ship that sails the wild waves of the academic seas. Unless….

What topic, more than any other, would be more appropriate to dive into for real if the starting point is this web of interconnections? After all, as I had read by then “Fight complexity with complexity”. First with careful, then with more steady steps. Or whichever word you use instead of “steps” if you’re at full sea. Destination: exploring, for better or worse, how the intuitive, non-tangible but nevertheless very real room for improvement for dealing with complexity in contemporary design engineering challenges might be discovered, developed, tried out and hopefully appreciated. With an open mind, and continuous attention for reflection. I had by then learned that much: in the face of complexity, you don’t look for the answer or solution, because there is none. But you can create an idea about the future (strategic intent), reflect on what is happening and how that aligns with your expectations and intent or not, and then decide how to move forward. An exploration driven by curiosity, not by wanting to find one ultimate truth.

To get the ‘academic party started’, together with the colleagues who had by then announced their willingness to be my promotors we drew up some tentative questions to start working with. As makes sense even more than before, these questions reflected not only the individual strengths and expertise that they brought in (academic, methodological, practice-oriented, real-life sensitive) but even more importantly the potential for sparkling synergy between all these strengths, to create an applied research setting that attempted to combine high levels of curiosity with a sense of both theoretical and practical grounding and a sense of structure from the beginning:

- How has complexity been described in design engineering literature?
- What complexity-acknowledging elements can be detected in existing methods?
- Are there ways how such elements might be enhanced or enriched in light of an ever globalising design reality?

- How do designers, novice and more experienced ones, consider complexity in the first place; how much do they consciously think about this?
- How can “dealing with complexity” be framed to provide actual guidance? Should that guidance be provided anyway or would it lead to too much rigidity?
- What arguments resonate with whom when suggesting that there might be room for improvement in the design domain at all? Who might get offended, (what) does that matter and how might this be addressed?

It was clear, these would not be the last questions but they sufficed to drive the first stage, to discover whether the free-of-obligation inquisitive stage of “on to something interesting” could be upgraded to the more academically formalised “definitely worth it to start the sailing the PhD-ship”. Therefore it became time to start thinking about how to set sail on this journey.

This would not be open-and-shut research. As first conversations with companies showed it would also not be easy to work with them in exploring this topic. Innovation, yes please. Novelty, sure. Actively embracing uncertainty, easier suggested than accepted. The gist of their response was that once we would have made clear progress on the road of demonstrating that our reasoning could work in practice, they might become interested to try it out.

Still, the way forward did slowly emerge: based on the explorations thus far it seemed feasible to work towards some propositions about next steps in dealing with complexity by design engineers. It was far too early to formulate hypotheses, i.e., expected and substantiated relationships between two or more theories. The research in this stage would still revolve around exploring ways to address a problem. Excavation of theory might very well result in clues but that is not enough to formulate hypotheses. With a good period of structured research, practitioners outside academics might become less hesitant though. So we would need cases to get empirical input that relates to the to-be-developed propositions. Now, there was a stroke of luck, because this is a university. And a university works with students, and students have assignments and are not as set in their ways as many professionals, while they are equipped with a backpack of existing design engineering methods. So they can compare, and thereby we can as well: how would they experience new suggestions on how to approach their global design challenges compared to how they worked until then, and what would be the effect on their results? Exciting, open, explorative questions, with a range of possible insights to relate to the propositions, with no obvious answers by any means. Even better, because of the direct involvement of design experts, both academically and professionally, in different roles during, before and after the student assignments, there would be a continuous check-back with ‘real-life’. One that would be less threatening to the professionals in companies. Excellent, just turned a disappointment into a strength for the research.

These would be the main ingredients to start off a PhD-journey. Final check with my promotors-to-be: did they dare to take on the role formally, to work with me and together? Yes, with eyes wide open and enthusiasm galore about this exciting shared journey ahead. Good to go.

Chapter 2

Chapter 2: Research framework, question, approach and methods

The story of the birth of this thesis was informally introduced, in narrative form, in chapter 1: The prelude. This included a first set of clues on why complexity, intent and a mindset that is both systemic and systematic are all relevant topics when talking about contemporary design engineering challenges. The prelude also hinted at the likelihood, based on numerous observations in practice, that there is room for further development in the arsenal of design engineers to in fact address contemporary design engineering challenges effectively in their study and work environments.

This chapter provides the conceptual basis for the rest of the thesis with regards to these observations. The next section 2.1 builds on the first chapter elaborating more in depth on the real-life context, in the form of the societal question and derived from that the main research question (MRQ). Section 2.2 then further explores several subject-areas, and thereby helps to shape the contents of this explorative thesis. The research approach and methods that are appropriate for the explorative research in this thesis are discussed next (2.3). A reading guide for the remainder of the thesis is provided at the end of this chapter (2.4).

2.1 Real-life context and main research question

This section briefly describes the context for this thesis. As announced at the start of the prelude, this will now be done in a proper academic and conceptual way, as opposed to the more personal introduction (Prelude). At the same time, this academic start of the thesis further expands the informal introduction. A level of (functional) redundancy can be observed between the two chapters. This is unavoidable and intentional. This chapter contains ample references for the observations that were mentioned in the prelude.

2.1.1 What is the observed societal problem

2.1.1.1 Initial focus and example

As chapter 1 showed the main drivers that have fuelled the birth of this thesis originated in particular in experiences with regards to emerging markets (i.e., non-OECD countries with high population and/or economic growth). In particular the types of issues that one might characterise as fundamental Quality-of-Life issues, which in fact are often related to the broad topic of sustainable development (Assembly, 2014). Such issues are for example lack of basic energy access, drinking water, sanitation and non-harmful cooking facilities and increasingly, lack of affordable access to financial services (Leke and Yeboah-Amankwah, 2018). In the IDE-faculty where this research was hosted, many assignments, including graduation assignments were conducted on issues like the ones mentioned. A large number of these are collected and discussed in (Kandachar et al., 2009, Kandachar et al., 2011). Since then the number of assignments on these types of issues has not declined by any means.

All of these issues touch on the matter of inclusiveness. The definition of inclusiveness by (George et al., 2012) is taken as a basis in this thesis: "the development and implementation of new ideas which aspire to create opportunities that enhance social and economic wellbeing for disenfranchised members of society". It is a topic that in the past years has received increasing attention in the domain of international development and global cooperation, foremost in the formulation of the Sustainable Development Goals (SDGs) that have taken effect in 2016. It is considered by some to be the most inclusive process ever as well (Coonrad, 2014), which apart from outcome is another level to consider (Papaioannou, 2014). Out of the seventeen SDGs five mention the term outright (4, 8, 9, 11, 16) and many (1, 3, 4, 6, 7, 8, 16) refer to a result that is to be achieved "… for all" which can be considered to imply the same.

The basic characteristics of the issues for which inclusiveness is an important consideration are that they are (very) large-scale, spanning entire and even multiple continents and they display quite different manifestations and contextual dynamics (Ubels and Jacobs, 2018). In that sense it is not too far-fetched to consider them complex. The main characteristics of complex problems or systems were informally introduced in chapter 1 and include: existence of multiple, diverse components and a multitude of interrelations between these components that are not always possible to observe, rendering the system as a whole unpredictable (Sargut and McGrath, 2011). The interrelations are both essential to consider (Monat and Gannon, 2015) and in the field of development, while they are not necessarily beneficial for different people (Andersson Djurfeldt, 2015), their existence cannot simply be ignored.

The differences, e.g. between the manifestations of what is broadly speaking the same issue, initially complicate efficient ways forward. This especially refers to the scale and the expected diversity in requirements when considering this scale (Kaplinsky, 2011). Therefore, in practice a form of simplification of the search space is often preferred. To manage the many uncertainties that can creep into the scope of the problem under consideration, that scope and thereby the diversity of involved stakeholders is then limited. While the former may be intentional, the latter might be a less intentional aspect. It however turns out to be quite relevant and implicitly reduces the value of the full width of knowledge to be included in terms of the range of its sources (Pagano, 2009, Hagel III and Brown, 2006).

In particular we often see how a focus on one particular context influences the subsequent process and the contents. As mentioned in chapter 1, in this thesis the working definition of “context” is a set of circumstances that together represent a particular manifestation of a problem and how it is experienced which as a whole determines eventual requirements for the solution direction. One easy and seemingly cost-efficient strategy is to develop a universal product (Bhatti, 2012), or to let the argument of a frugal design justify focus on maximising cost reductions (Zeschky et al., 2011, Brem and Wolfram, 2014). The other main strategy is to use contextual intelligence to ensure proper understanding of contextual specifics (Khanna, 2014, Peša, 2017) to feed into the development and design process. As a mostly unintended side-effect, exactly because of that argument, this focus appears to be non-conducive for the solution at hand to reach a wider audience (Kaplinsky, 2011).

A representative and evident example of the strong influence that contextual intelligence has and what the consequences are can be found when we look at the domain of clean cooking, with introduction of improved cook stoves (ICS) as a primary physical element in that domain.

> *The domain of clean cooking for emerging markets has in the past few decades been an attractive one for socially minded companies and designers. The negative societal impact of biomass-based cooking on open fires or simple cook stoves is considerable, as can be seen in many numbers, for example – all on annual basis - four million premature deaths* (WHO, 2016), *100 million DALYs (Disability-adjusted Life Years) caused by an assortment of health problems* (WHO, 2016, Mandelli et al., 2014, Lin et al., 2016), *3% of global CO_2 emissions, 25% of black carbon, deforestation* (ESMAP, 2015) *and many second order effects. There is much opportunity to achieve positive impact in terms of health (lower harmful emissions), economic considerations (higher fuel efficiency and therefore lower fuel costs), and ecological effects (reducing deforestation and greenhouse gasses). Secondly, cooking is a culturally specific, and therefore people-driven activity. The industrial design domain prides itself on being human-centred* (Norman, 1988). *The clean cooking sector has seen its share of technology-push driven initiatives* (Thacker et al., 2014, Bielecki and Wingenbach, 2014, Abdelnour, 2015) *where user-requirements were not evidently taken into account. It therefore makes sense that design engineers get involved in developing improved cooking eco-systems, including but not limited to designing cleaner cook stoves that are geared towards user-neds and behaviour. The aim is to people in dire need who lack means to address these needs, i.e., who are disenfranchised* (George et al., 2012). *These efforts therefore also consider the inclusiveness aspect.*

Another realistic observation is that the majority of the projects regarding improved cook stoves that did take human requirements into account, as opposed to using the technology as main driver, was executed with a particular target group in mind. This was already an improvement relative to the preceding efforts that did not take users into account (Tesselaar et al., 2013). However, in practice the cook stoves that were designed and optimised for a primary target group often with the aim to scale roll-out of the stove after initial success, often did not fare well after the – donor-funded - pilots had been assessed as successful (Urmee and Gyamfi, 2014). There are many factors that can help determine whether an innovation (social and/ or physical) becomes a large-scale success in terms of impact, and the design engineering approach cannot influence all of these. Reasons for non-adoption can be many, including ignorance by designers and development practitioners of the (hidden) value that existing practices and devices have for the people who are targeted (Khandelwal et al., 2017).

When we look at the overarching results of all these efforts, through a quantitative lens, we see the following: by 2015 the cumulative number of distributed cook stoves was 82 million, which looks sufficiently impressive. Of that total number 53 million were considered clean or efficient, within that number, 23 million were assessed as both clean and efficient (Lombardi et al., 2017). A quick calculation (Kersten et al., 2017b) shows that this means about 4% of people that suffer from the effects of dirty cooking have been reached. This leaves aside the discussion that is facilitated by the Clean Cooking Alliance, or its previous name the Global Alliance for Clean Cookstoves, on how 'clean' and 'efficient' cookstoves need to be to receive these labels (GACC, 2016) Additionally, "distributed" does not necessarily mean "adopted by the market", i.e., people may have received a cook stove but whether they use it is another matter. All in all, while certainly progress has been made, given the full scale that the issue is suffered on, it is safe to say that many people worldwide still await an effective clean cooking solution that is appropriate for their circumstances.

2.1.1.2 Observed consequences

The common product or solution development strategy to focus on one particular use case in some instances did result in funder buy-in, because a proof-of-concept had been shown. In relation to the design domain, such a (common) strategy is indeed encouraged by concepts like human/ end user-centred design and design thinking principles (Brown, 2008, Brown, 2009): do a deep-dive with the specific target group you are focusing on to develop and test a solution that effectively meets their real needs. The developed product or solution is then typically, together with representatives of the foreseen target group, in several iterations optimised further (Ries, 2011). In practice these iterations can also allow for perspectives of other stakeholders to be taken on board, if they are considered relevant for the target group. How broadly such perspectives are sourced depends on the designer.

It is however not evident how far away from the initial scope, i.e. the specific manifestation of the problem, or context, these perspectives are sourced. The farther away from the primary context, the more diluted such perspectives might be seen in relation to the allegedly more relevant contextual intelligence (Khanna, 2014). The process of sourcing in reflections and perspectives is then easily “closed down” to not delay the process (Stirling, 2008). While one might initially assume that incorporating perspectives from outside the aforementioned initial scope dilutes the task at hand, a question can be raised whether these perspectives might not also *enrich* the overall view on the problem. This is one of the points that this thesis in fact puts centre stage.

Another observation related to this strategy is that early simplification, i.e., using a limited scope with regards to target groups and thereby choosing a particular manifestation of the broader issue, creates a practical, well manageable and seemingly efficient pathway (Chen and Crilly, 2016). The other side of that coin is however, as has been abundantly shown in practice, that a result that may work well within the limited chosen scope does not easily lend itself for scaling. This is valid for the ‘quantitative’, business-like interpretation (selling more products) as well as the more social association (creating more impact). The limitations in terms of scalability have become apparent both on product level (Bocken et al., 2016) and on organisation level if aspects like local autonomies (Bradach, 1997), emergence and self-organisation (Iñigo and Albareda, 2016) are not adhered to. The question of what is being scaled in the first place, i.e. products, organisations or impact, is not always explicitly considered (Ubels and Jabobs, 2016, Ubels and Jacobs, 2018). In short, scaling, both of product quantities and impact, unleashes forces that are not easily predictable (Wigboldus and Brouwers, 2016) and this is not always acknowledged, hence frustrating attempts to achieve societal impact on a substantial scale. It is one of the many ways how the phenomenon of complexity manifests itself; this will be revisited several times in this thesis.

2.1.1.3 Focus in light of the global playing field

The observation of similar issues with different manifestations worldwide is a specific form of a larger trend, being globalisation. Globalisation is nothing new, it has in many shapes and forms existed for millennia as will be discussed further in chapter 3. In particular after WWII the ubiquity and influence has increased dramatically. This in part strengthens the claim that even while cultural differences matter, attempting to ‘solve’ a contemporary large scale issue is doomed to fail if the – obvious and hidden – connections between manifestations are not taken into consideration (Stacey, 1996). The many connections and their “mutual interdependencies” (Thompson, 1967) are both cause of the pervasiveness and reason why these types of issues cannot be ultimately solved (Rittel and Webber, 1973). But if we do want to stand a chance in creating a better understanding on how to address them, we better consider the large system (Blizzard and Klotz, 2012), and consider a more diverse ecosystem of stakeholders (London and Hart, 2004, Nieto and Santamaría, 2007, Mudambi et al., 2007) before we make the big consequential choices. In that light, it seems to be increasingly relevant to acknowledge that the diversity of stakeholders, even with the best intentions, is still often limited to the ones from a specific context or use-case (Taysom and Crilly, 2017), very strongly connected to one’s own circle (Tett, 2015, Sunstein and Hastie, 2015) or too much confined to a specific type of person (Suen, 2015).

One might raise the point that a similar situation can be the case for problems or situations that do not refer specifically to quality-of-life struggles. This is certainly a valid point. What can also be observed in these cases however is that accepted strategies exist that can sufficiently address this situation (Dahlman et al., 1987, Harrison et al., 2009). That situation might be summarised as “No dire problem, but abundance of time and money”. This opens the door to the following strategies: 1. Feature overkill: to allow for a wide diversity of possible requirements, a large number of features is built in or prepared for, which the target groups can afford or afford to tolerate. Examples are pre-installed apps on smartphones and generally unused functions in software programs. 2. ‘No worries redesign’/*indifference*: If still a substantial redesign is necessary this is not considered a big problem in the sense of societal impact because the product is merely addressing a ‘luxury’ problem. And even if there is a societal aspect delay does not cause dire negative societal impact like losing lives. One example would be luxury yachts which can be fully tailored to individual and partially unforeseeable whims. This causes a delay in the adoption but one would be hard-pressed to claim that this is detrimental to society at large.

Similar considerations are possible to guide discussion on the differences between topics and problems that refer to sustainability or not. An issue that can be worked on can refer to 3BL, triple bottom line (Elkington, 1998) or not but still be challenging. Meaning, a situation that does not specifically refer to the triple bottom line theme can still be an option to focus on. Having laid out these different possible focus areas, which of these types of situations would be more interesting to choose for this research?

To clarify the playing field for this question, and thereby making the choice more easily understandable, Figure 2.1 includes the above-mentioned dimensions as axes of a 2x2 for the decision where to focus. As a reminder of the terminology that is included in these dimensions: “3BL” on the horizontal axis refers to the aforementioned triple bottom line interpretation of sustainability, "affluence" on the vertical axis refers to affluence level of the target groups that experience the problem at hand. Low-affluence end-users in the context of emerging economies are often referred to residing at the BoP, Base of the Pyramid (Hart and Prahalad, 2002, Prahalad, 2009), and targeting them falls under the theme of "inclusiveness", which is why these terms are relevant for the lower two quadrants. The choice that was made as focus for this thesis is depicted by the circle. In the next section this choice is discussed more in depth, including why it makes sense for this particular thesis.

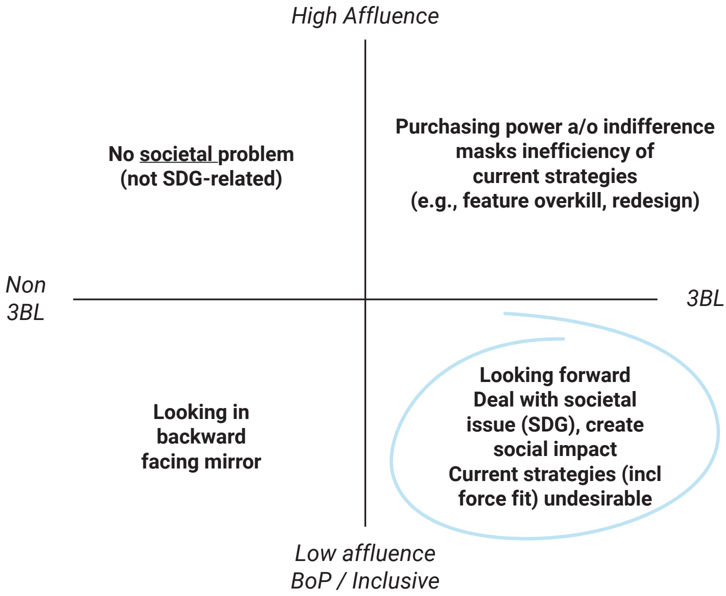


Figure 2.1 Focus for this research

At this point, i.e., when discussing the scope, a one-time 'disclaimer' is added. It is a relevant note, it will however not be discussed again and again throughout the thesis because it would distract too much. The note is this one: the academic domain that is the main angle of this thesis is design engineering. That domain is not the sole factor to determine whether something will be a success, in terms of product adoption or impact, on a large scale. As has for example been discussed by (Banerjee et al., 2017), in the context of policy scaling, there are many challenges that affect how a successful pilot success might (not) translate into a successful scaling effort. They mentioned six particular challenges: market-equilibrium effects, spill over effects, political reactions, context dependence, site-selection bias, and general large-scale implementation challenges. Of these, the final three, the final one only lightly, are included in this design engineering-oriented thesis.

The full list, and there are more possible challenges that can be thought of, demonstrates that the scope of this thesis can never be to encompass the entire scaling universe, nor could that therefore be the intention, nor should it be the (hidden) expectation. The thesis only attempts to explore how an evolution in thinking in the domain of design engineering might *contribute* to arriving at more effective approaches to achieve societal impact on a large scale. The undeniable reality that a product engineering angle is not always a justified component of a development process in the first place (Khandelwal et al., 2017) is a relevant notion, but not the focus in this thesis.

2.1.2 What are arguments for the research: why does this problem matter?

To understand the choice as highlighted in figure 2.1 and thereby the width of the scope for this research, it is relevant to realise that the source for this thesis is the Design for Sustainability section of the department Design Engineering. In concrete terms this means the section that is most focused on product development with a sustainable mindset, including (but not limited to) products and services for pervasive issues in emerging markets that aim to improve the lives of people categorised as Base or Bottom of the Pyramid, where the problems are dire and resources few. These are the situations and target groups that are typically implied when the term “inclusive” is being used (George et al., 2012). In short: the results of the design assignments and research that are executed in this section are directly aimed at creating a positive societal impact, from the perspective of a contribution by design engineers, in emerging market context (Kandachar et al., 2011) and for people who are facing daily-life related struggles and who are mostly excluded from current ‘solutions’ because these have not been geared towards their possibilities or capabilities (Oosterlaken, 2009, Mink, 2016).

Seen from these angles, history has shown that many approaches that were used thus far are to such an extent aimed at achieving success on the short term, that they hurt the scalability of products and therefore also the entities that attempt to implement them (Ubels and Jacobs, 2018, Zeschky et al., 2011). This may even result in companies simply focusing on markets that pose them with fewer problems (Qiu and Fan, 2013). It is possible to have a small scale viable initiative specifically geared towards a particular small scope and nothing more, but that is very rare. Generally economic viability for providers requires a certain scale that brings production efficiencies, literally economies-of-scale, that can then lead to lowering prices for beneficiaries. Often the argument is used that a precondition for successful scaling is simplicity: what is being offered should be close to what people know and the way how that offering is organised as well (Hartmann and Linn, 2008).

Indeed, only if a serious large-scale issue is addressed at a substantial scale can real social impact be achieved. This is where societal and business goals can meet (Koh et al., 2014). For those sensitised by a sustainability mindset this does not come as a surprise. After all, sustainability is also more the property of a system and not of individual elements (Ceschin and Gaziulusoy, 2016). Still, in both cases it is quite doubtful whether a mindset of maximising simplicity is generally the right response. Because there is also another way of looking at it, namely that sustainable development is not the search for one perfect equilibrium (i.e. solution), but nourishing the ability to explore options and adapt (Allen, 1998).

As we have observed, because of reasons of perceived control in the process and therefore outcome (Mundy, 2010, Chen and Crilly, 2016, Backx et al., 2017) and a sense of clear accountability (Hartmann and Linn, 2008), problem formulations are easily driven by reductionism (Nelson, 2007) and analytical instead of hierarchical decomposition (Diethelm et al., 2016). Additionally, complexity is sometimes suggested to be tackled by taking small single steps at a time (Norman and Stappers, 2015). While from a pragmatic point of view this seems understandable, the idea of control is probably illusionary anyway (Flach, 2015). One consequence is that needs of target groups who are not within the initial design scope are often not taken into account, as we can amply see in practice (Kaplinsky, 2011, Kersten et al., 2017a, Kersten et al., 2018a, Kersten et al., 2019b). This unfortunately hurts the scalability or at least it causes a serious delay in taking the steps necessary to achieve substantial scale. For the pervasive issues that were mentioned these delays cost lives. This is, once again, one primary driver behind the chosen focus: if foreseeable manifestations of needs that do however not have immediate priority for the provider of the 'solution' to take into account, the delays that follow when turning to the target groups that have these needs cannot be justified in terms of casualties (Koh et al., 2014). Some earlier work at the same faculty as where this thesis was written hints at this necessity to look broader (multiple contexts) and not just deep (one context). In work of (Van der Kleij, 2008) and before that the subsequent work of (Ideler, 2006) and (Wong, 2007), the latter two specifically on design of cookstoves for target groups in different countries, the relevance of multi-contextual awareness is demonstrated and to an extent used. In these initial efforts the need for adaptability was stressed as one of the outcomes of their research, but this has not been turned into common practice yet, also not by their principals.

There is another consideration, one that feeds on a phenomenon on the opportunity-side: if needs of more target groups, i.e. representing multiple contexts, are actively taken into account it is possible that the collective intelligence that is brought together creates a design space where the acknowledged interconnectedness between this intentional diversity of insights "productively feeds into" a flow that improves the quality of the design process and its outcomes (Morin, 2008). *Not* making use of such collective intelligence can from that point of view therefore be seen as a lost opportunity or formulated more prosaically “mutilate the web of interconnections that weaves complexity” (Montuori, 2011).

Once this logic is accepted, a derived argument for devoting research to this problem is that addressing it needs to be invoked sooner rather than later. In other words, to make sure that diversity and scalability to address large scale issues are conscious concerns for design engineers, it is not difficult to see that design education might need to pay attention to this. By including the suggestion as emerges from the above – i.e., in a *systematic way vary the contextual sources* for *inputs of the design process* at the *very start* - in the training of design engineering graduates, professional environments stand to gain and can be easier enticed to start working in similar ways. Using experiments in design engineering education might then be an important element on this path. One might call this “look before you leap” or perhaps even more aptly, “look in multiple directions before you cross a street” (Kersten et al., 2019b).

While the arguments why the topic as stated might already resonate with some factions in non-academic professional environments, in general approaches that depart from existing norms are not accepted easily (Kaufman and Gregoire, 2016). To help build the case towards professional decision makers to adopt any novelty that they are presented with, some grounding in empirically based academic research can help to challenge existing norms. As we all know, innovation thrives on ‘failure’ and learning, so being open to new thoughts can – if nothing else – be seen as an opportunity to learn more (D’Souza and Renner, 2014, Montuori, 2012). This thesis intends to provide a basis for that learning.

2.1.3 Main research question

The preceding sections describe the societal problem, and therefore hint at the practical relevance of addressing it. To address the societal problem from an academic perspective it must be translated in a research problem as well. The main research question that follows from the identified societal problem is stated below.

> *Which theoretically and empirically supported insights and knowledge can be generated with regards to a design engineering approach that uses systematic variation of contexts before the design task has been set, in order to address, in particular, multi-contextual complex issues in society?*

To provide further focus and clarify the emphasis for this research, two main angles are now introduced. These angles will guide the scoping of the literature research, and help to structure the findings, discussion, conclusions and recommended next steps.

1. **Design engineering arsenal**: based on our knowledge of the current arsenal of (systemic) design approaches and tools, what can an approach with the focus as expressed in the MRQ add? To assess this, some constructs are likely to be relevant, and therefore deserve closer inspection. These constructs are chosen after the extensive literature research and will be outlined at the end of chapter 3.
2. **Empirical framing:** in the faculty and section where this research is hosted, the types of issues addressed concern sustainability (impact) on a large scale and inclusiveness, which often imply complexity. The category of quality-of-life issues, related to sustainability and inclusiveness is the main focus area for this research, as clarified in figure 2.1. Factors that lie beyond the direct sphere of influence of design engineers are not included in this thesis. To venture nevertheless a little bit beyond the direct borders of the design engineering domain, an adjacent field that *is* feasible to take into consideration is the one of management. To increase the chance that a change in design engineering practices, to be explored in this thesis, can contribute to achieving large-scale impact, this thesis will consider how changes in product/ service development could be aligned with management considerations and decision making with regards to taking a longer term view (implementation in multiple contexts). Furthermore, because of the choice for the focus of the empirical part of the research (see Research approach), the implications for design engineering education are investigated as well.

As a general note for the use of the term "framing", since to some people it might have a negative connotation: in this thesis it refers to the neutral notion of "effectively communicating, formulating, emphasising certain aspects".

The aim is to investigate whether such an approach would result in *appropriate design outcomes in the face of complexity* and if possible gain insights in the conditions when that would most likely occur. The goal is not to 'prove' that any individual approach is the only or the best one for the design challenges that this thesis focuses on. The goal rather is to explore whether the promising signs stemming from the early research hold up when these signs are more thoughtfully scrutinised (theoretical angle) and tried out (empirical angle).

The explorative nature of the topic does not allow research questions that focus on proving specific testable hypotheses. That would have required existence of clear relationships between two or more theories, which is not the case yet. Also, testing such hypotheses, deductively, would require large data sets based on comparable real-life situations. These are not realistically available.

The research approach was therefore primarily inductive and aimed at identifying patterns that suggest how existing theory (and practice) might be enriched, as opposed to a deductive approach where existing theory is decisively tested. The linking pin in this approach is the use of propositions that are based on theory. These propositions are not, cannot and are not intended to be, falsifiable or testable like hypotheses for the reasons described above, but they are less soft than corollaries. The propositions are elaborated upon by means of cases from real life. More details about the approach are provided in section 2.3.1. The results of the elaboration are not intended to be the endpoint but to direct further inductive research.

2.2 Areas for further exploration

The main research question, as it should do, raises many possible side-questions and directions for research. To further guide that research, this section provides an introduction to the key components, roughly following the underlined words in the Main Research Question, and the main angles as mentioned in section 2.1.3. The first explorations in the next few sub-sections will help to set the scene for the research approach that follows and help to outline the themes that require and deserve fuller investigation in the literature research in chapter 3.

2.2.1 Conceptualisation of main design engineering characteristics

When we are talking about a design engineering process it is relevant to have some shared understanding about what it is (definition) and what its main characteristics are. In terms of the definition, an entire encyclopaedia might be filled with different versions. Given the context of this thesis, it makes much sense to use as starting point the one provided by the – academic - godfathers of systematic design engineering (Beitz and Pahl, 1992): “Apply scientific knowledge to the solution of technical problems and then optimise that solution within the given material, technological and economic constraints”.

This definition, as they formulated it, can already be considered as a modernisation at that moment in time. In particular it lightly incorporates the view of (Simon, 1969) that designers can no longer strive to maximise one product-performance dimension but have to combine several dimensions. However, he intended this combination to occur not by means of optimising but through satisficing. To reflect additional main insights from the past in order to arrive at a further modernisation of the definition, the following observations are relevant:

- the economic constraints that are mentioned should by now be interpreted broader. In light of across-the-board changes in society, social and ecological constraints now will have to be added. The rationale for this can be found in 2.1.1.
- whereas in earlier eras design engineering indeed primarily referred to technical problems as included in the definition, by the current 21st century this is no longer an appropriate restriction. The nature of problems has evolved, and thus also the role of design engineers and scope of the design engineering domain. This aspect is elaborated in 2.2.2 and 2.2.3. In line with the name of the faculty where this research was hosted, the term design engineering, and not design, will be used in the remainder of this thesis. This in fact reflects the view that design *engineering* has evolved.
- as is explained elsewhere, one implication of society becoming more complex and design challenges therefore as well, is the fact that we cannot strive for solutions. While it may sound unfulfilling to some, complexity by definition cannot be solved and attempting to do so and thereby framing a design task as such is counter-productive.

In light of these addendums to the original definition by (Beitz and Pahl, 1992), the revised definition that for now is proposed is the following, with revisions underlined: "*Apply scientific knowledge to <u>understanding of and subsequently addressing societal problems</u> in order to <u>satisfice towards a better future</u> within the given constraints (material, technological, economic, <u>social, ecological</u>)*".

Apart from definitions, for the purpose of this thesis it is even more sensible to spend some time on characteristics of a design engineering process. In agreement with (Leenders et al., 2007) and (Muller, 1999) the ones below are in this thesis considered to be main ones. These implicitly reveal some differences between a *design process* and an *analytical process*. Importantly, any design engineer makes to some extent use of all these characteristics but the use and insight in how the different characteristics are interrelated may sometimes occur unconsciously. Some examples of this interrelatedness are mentioned in the text below.

<u>Systematic variation</u>: Most likely this is the oldest characteristic, dating back to Leonardo da Vinci. Prior to him design-like activities mainly occurred through more or less random trial and error, perhaps for artist-designers more driven by feeling than knowledge. As we know from his writing and sketch-books and other sources, see e.g. (Isaacson, 2017), he seems to have been the first to introduce a form of structured, i.e., systematic, trials both in art-works and engineering. This refers not only to his own activities but also to the cooperation with others, e.g. pupils: as a team often variations on the same theme were tried out. In his case this was mainly focused on the 'solution' process: laying out a high level design and then filling in the details in a systematic way, using small variations to get to the best overall design.

Hierarchical decomposition: in the basis this characteristic refers to the sub-division of a problem into smaller sub-problems that can be associated with (smaller) design tasks that focus on a sub-problem that are easier to oversee and manage. If this division would happen non-hierarchically, the solutions to each sub-problem cannot be put back together because the basis for separation (division) is unknown. Therefore, a form of *hierarchical* decomposition is necessary. That is however not the end of this story. In the context of this thesis, it is relevant to mention several other notions about this characteristic because without proper understanding of these notions, next steps are unlikely to resonate. One example is then added to clarify how these notions can be used in an integrated way.

- Like mentioned above, if you do not consciously know where and how you divided the overall problem into sub-problems, constructing any overall integrated improvement ('integrated solution') is impossible unless by means of time-consuming trial-and-error.
- Decomposition can be done into sub-systems and/or aspect-systems. Sub-systems refer to an entity or a set of inseparable entities that belong together and can literally be taken out of a system as a component, for example the engine of a car. Aspect-systems refer to the *relations* between components. In the example of a car an example of an aspect-system is the set of properties that determine the aerodynamics. This cannot be taken out of and put back into the car, the relations transcend entity boundaries (Kramer and de Smit, 1979).
- Because sub-systems can be distinguished and separated (also in a physical sense in case of products) while aspect-systems cannot, it is much easier for humans and certainly engineers to work with and think in terms of sub-systems when decomposing a problem than to think in terms of aspect-systems. Whether "easier" equals "better" is a whole other matter.
- When talking about developing 'solutions' or improvements, sub-systems are investigated and optimised according to product requirements, putting the performance of the (physical) component or set of components that belong together centre stage. Aspect-systems are optimised according to design requirements putting the optimal functioning of their *relations* and thereby the full system centre stage. Obviously, this is not binary: improvements on sub-system level in practice will be developed with some notion of the fact that they need to work together with other sub-systems. The emphasis does however strongly influence the way how a design engineering problem is being approached.
- Which brings us to the all-important *synthesising* notion: if you decompose a problem based on aspect-systems, the inherent attention for interrelations increases the chance that the improvements work on the full system level; satisficing considerations

(see next characteristic) are already built in because integrative thinking was unavoidable in the first place. Accepting that base reality leads to improvement directions that are inherently more systemic because you explicitly recognise interrelations and therefore are more likely to build towards overall results that are superior on the level of the full system/ problem.

How does this translate into practice? An example:

Decomposition example: *When the challenge is to design and manufacture a car in such a way that it can reach higher speeds than a previous model, you can decompose it into sub-systems (wheels, engine, suspension, brakes) or into aspect-systems (aero-dynamics, road-friction, energy conversion, power/ weight ratio). You can put together variations of optimised improvements of each individual sub-system and hope it results in a faster car but most likely when putting together the different solutions that were optimised on sub-system level, you will have to satisfice or even compromise to let them work together in an actual car. A possible result is that the different optimised improvements on sub-system level (slicker wheels, larger engine, less powerful brakes etc) do not work together well on system-level (i.e. the car, circumstances in which it is used and the handling by the person driving it).*

Improvements to aspect-systems (aero-dynamics, power/weight ratio etc) cannot be physically put together as easily, but the improvements in the different aspect systems (less wind resistance in the overall design, strong light-weight materials to support an engine that uses regenerative power etc) already took into account the veins (relations, connections) between different sub-systems. The overall improvement is therefore (much) less likely to require many late-stage changes and rethinking, and is therefore likely to outperform the car that is composed of sub-system based optimisations. And quite likely against lower overall development costs.

Satisficing: for simple problems the human mind may still be able to analyse and come up with optimal solutions. There are hardly any design challenges that are simple anymore. This implies that we experience something called bounded rationality (Simon, 1969). Therefore, when engaged in non-simple solution development, a third characteristic of a design challenge comes into play, satisficing. It is almost certain that each sub-problem has multiple potentially valid solutions. When putting these together to create a coherent integrated solution, e.g. by morphological synthesis, many different combinations can be formed. Since it is not possible to determine the optimum solution with that many variables, the designer has to satisfice, i.e., determine which combination of partial solutions meets at least the minimum requirements from each perspective (requirement) and then try to improve further.

A second level of satisficing refers to time: with infinite time available, there are also infinite variations of solutions available, which does not help in practical situations. In practice time is a finite resource and thereby a realistic constraint in a design process. In a situation with many different variables (requirements), design engineers with a mindset that is geared towards finding an optimum are not likely to flourish both in terms of making actual design choices and the time they spend on making these choices.

The prospect of having to meet many different requirements at the same time can easily encourage a designer to formulate the design task in such a way that the number of variables that should be taken into account is reduced, i.e. the design task is reduced to an intentionally more manageable, narrow, scope, most likely governed by division into sub-systems, with focus on one sub-system (e.g. use-case). As mentioned before, the design characteristics as discussed here are – sometimes unconsciously – intertwined. For example, because of the fear of the need for (too much) satisficing, there is an incentive to decompose the problem/ system into sub-systems. This leaves room for systematic variation within the design task, and immediately reduces the scope of that same design task as well.

<u>Discursiveness</u>: finally, a characteristic that should be most recognisable to design engineers, but can be interpreted in different ways. So bearing in mind the intended interpretation for this thesis justifies the explanation: a design engineering process is seldomly executed in a linear way. The real process, also in a psychological sense, involves iterations, loops, quick thought experiments, perhaps low-fi user tests, jumps back and forth and so on. In the end all design activities are executed but in practice hardly ever in one given, rigid let alone linear sequence. That is the core notion of what is called discursiveness in this thesis. The more *formal accountability* of, i.e. reporting on the results of, a design process is often done in a more chronological sequence: you cannot build a prototype if you have no idea what the problem is, you cannot check the compliance with design requirements if these requirements have not been specified yet and so on. There is a certain logic, i.e. linearity in the design process as it has to be *accounted* for, i.e. reported on, but the designer's *actual reality during the process* is likely to be more 'chaotic', i.e. non-linear. This differs from an analytical approach where hypotheses are tested in a linear workflow. This difference has many implications for concepts like plans, planning and so on. It might be fair to say that the more challenging or complex a design assignment is, the higher the likely degree of discursiveness as it is explained above.

The regular design engineering process (R1.0), including a version of the totality of these characteristics and their interplay, is shown in figure 2.2 below and is used by many designers, inside and outside Delft, e.g. (Roozenburg and Eekels, 1995). To be clear, design engineers use a range of methods and variants of this process. Many of them are shown and explained in more detail in the Delft Design Guide (Boeijen et al., 2014, Van Boeijen et al., 2020, rev. ed.). The figure below refers to the most commonly known version of the process, which is appropriate to serve as benchmark for visuals in later chapters, to start with at the end of chapter 3. It is both useful as well as a given that design in essence refers to *transforming* (T) *an existing situation* S *to a modified more desirable one*, *i.e.* S^1. Since this is a given, this will not be included in the figure below nor in subsequent versions.

To briefly highlight the occurrence of the design characteristics: *Systematic variation*, visualised by the three delta-signs (Δ), occurs (potentially) during several activities within the design process including different *decompositions to be tried*, *devising partial solutions (morphology)* and *composing integrated solutions*, all within execution of the design task, which influences the overall set of requirements *discursively*, while a level of *satisficing* will be required both when composing integrated solutions and deciding on the final solution. The arrows between the left and the right part of the visual imply a continuous iteration between the reality of the design process and the changes in the *living document* that contains the list of requirements.

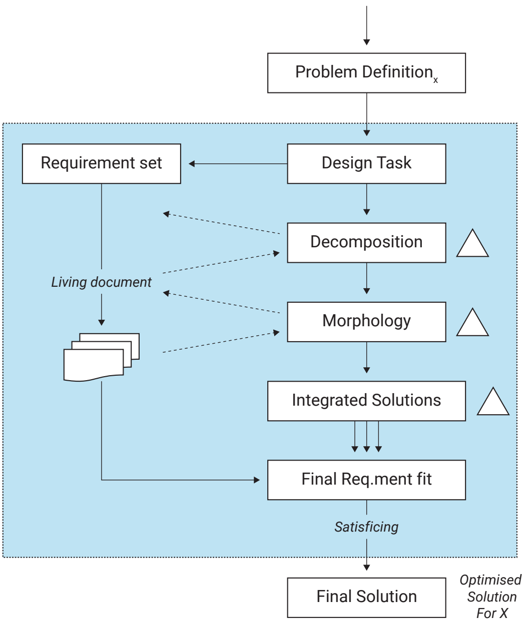


Figure 2.2 Regular design engineering process (R1.0)

At this point it is relevant to get a sense for the way how systematic design engineering methods have evolved thus far and thereby shaped this current design practice.

2.2.2 Evolution in systematic design engineering methods

As has been noted several times, it was clearly observed in practice in the period that was described in the prelude of this thesis, that potentially broad ranging design assignments are often simplified or decomposed in one way. In other words, the design task that is defined is often chosen to be too small or simple in relation to reality, based on decomposition in sub-systems. A design task will almost always be smaller than the perceived problem in all its aspects. However, decomposition into easily distinguishable sub-systems or too simplistic aspect-systems implies that in the face of daunting complexity a design task is formulated such that the designer can focus on a particular manifestation of a problem that is to be addressed, e.g., focus on a specific target group in a specific context, or "one use-case" in design terminology.

Then *within* that scoped design task systematic variation does often occur, in particular when composing integrated solutions from a range of alternative partial ones. In rare cases the strategy is chosen to vary the decomposition of the formulation of the problem, for example by spending extensive time on (re)framing (Dorst, 2006, Paton and Dorst, 2011, Dorst, 2015), looking at the problem from different perspectives, within the scope of the (assumed) use case.

When looking at the history of design engineering methods, we can see how a number of waves have made the design engineering process more systematic in nature (Beitz and Pahl, 1992). We can roughly see three waves:

1. Leonardo da Vinci: this quintessential artist-engineer has demonstrably pioneered systematic variation, primarily to devise alternatives for partial solutions – artistically and engineering-wise - and then create multiple variations of an overall solution, as input to choose the most suitable integrated one. This both explains and justifies inclusion of his name in the title of this thesis. As a side note it may be interesting to know that pure artists like Pablo Picasso also used the practice of systematic variation, although the public mostly only sees the one end result of their process.
2. From the world wars onwards emphasis was put on systematic optimisation, in particular by decomposition in clearly distinguishable sub-systems. These systematic optimisations were then aimed to be combined and create sufficient overall optimisation.

3. From the late 1960s onwards social and societal relevance of design engineering started to rise on the agenda. This brought with it relevant but uncomfortable factors to be taken into account like bounded rationality (Simon, 1969) and ‘wickedness of problems’ together with insufficiency of top-down planning in addressing large-scale societal issues (Rittel and Webber, 1973). In parallel, the general concept of systems thinking started to gain traction. All of this paved the way to pay more attention to relations (e.g., the aforementioned aspect-systems) and later on the more social aspects of design, and design engineering. One effect of this evolution was the attention for specific needs in resource-constrained situations, first context-specific and later with nascent attention for the phenomenon of multiple contexts.

Section 3.1 will provide a more extensive historical overview of systematic design engineering methods, and sections 3.2 – 3.4 address the broader business landscape. In figure 2.3 below, a simplified preview is provided that helps to set the scene for that deliberation. It is intended to show the dominant external drivers during different periods (non-linear Time, x-axis), vis-à-vis the level of (non-linear) societal complexity (y-axis), through the lens of design engineering. The three waves mentioned above are represented by the half-ellipse shaped arcs.

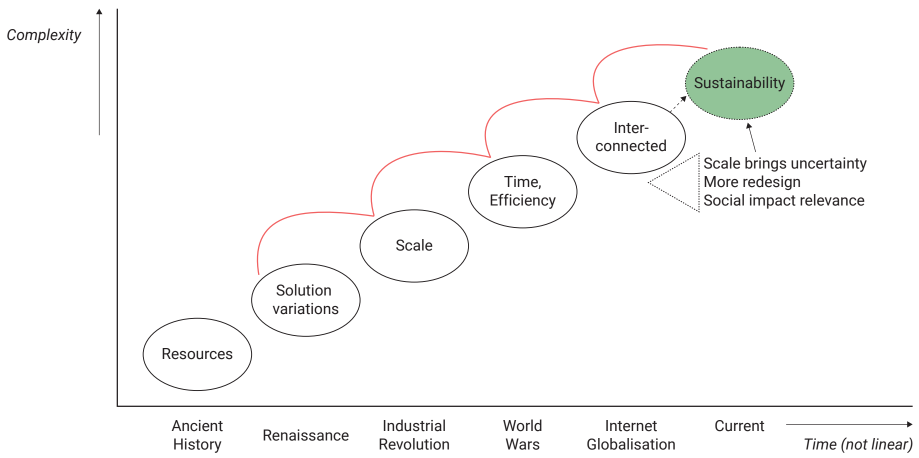


Figure 2.3 Main external drivers to shape design engineering, what might be next?

As this preview shows, when looking at this historical evolution, it seems a sensible question to ask what might be a next step, as seen from the angle of adopting systematic principles. As the figure suggests, the challenges in the current period - increasing uncertainty that comes with a global scale, the observed design practice of frequent redesign and the increasing importance of social impact - should ideally be addressed in that next step. The central theme in that next step, to the top right, might therefore be summarised as *Sustainability*.

2.2.3 What room for additions and further evolution can be identified?

Having described main design engineering characteristics (2.2.1), and having sketched a rough preview of the evolution of systematic methods in design engineering (2.2.2), a few patterns are emerging that build on these first two layers of understanding. In particular the oldest design principle of systematic variation catches the attention.

When we look at the design processes that aim to address basic quality-of-life issues, the characteristic of systematic variation within the design task can easily be observed in many outcomes of design assignments. What can also be recognised is that because of the obvious large-scale nature of these issues, an almost unanimous and mostly conscious choice is made by design engineers, their managers and others, to not attack the whole problem in one go, but go at it with small steps, by dividing the larger problem into sub-problems, most often resulting in choosing one particular use-case as scope for the design task. The choice for that particular use-case may, but may also not, be the result of a systematic process, e.g. by determining the size of the different groups, or the access one has to each group, or the severity of the issue as experienced by different groups. The main point is that the choice is made as one of the first ones before proceeding.

In practice another reason that such a focus is applied is the perceived overwhelming nature of the complexity of the issues as they are (technical, social, political, economic, ecological) so combining such aspects from multiple contexts would be 'unbearable'. This directly results in a focused, but simplified design task. Some already warn for the potentially disastrous consequences of approaching reality in this way (Probst and Bassi, 2014). Even more, if looked at from the opposite perspective, the complex circumstances might also be seen as a reason to work *with* this complexity, i.e., look for the *opportunities* in the connections (Sargut and McGrath, 2011, Monat and Gannon, 2015, Wheatley, 1998).

A very likely result of the one use-case strategy, as can be seen in many different cases in practice, is the mismatch or force-fit of the product with new groups of end-users and beneficiaries, the non-initial use-cases. Examples of such products where this has clearly occurred are cook stoves, as was demonstrated in 2.1.1, and the myriad of devices to clean water to turn it drinkable or sanitation, see e.g. (Mink, 2016). The understandable, pragmatic approach to start small and manageable (Lindstrom, 1959, Ries, 2011, Norman and Stappers, 2015) and pivot in small steps until a first success is achieved may however have undesirable drawbacks as well. If not balanced by a level of longer term intent, this approach may lead to design "heads down in the engine room of the problem" (Myerson, 2015). Thereby this approach inadvertently contributes to pragmatic path-dependencies and lock-in with regards to the chosen solution (Jones, 2015). The direction that is guided by the investment that follows the first step that is deemed successful then becomes difficult to depart from, both in financial and design-psychological terms. First success, whether more or less accidental or not, dampens the thirst to remain curious. And if we quickly return to lessons we may take from Leonardo da Vinci, we might in this case be reminded of the adage "Don't take Yes for an answer (too soon)" (Gelb, 2009). For cases where end-users and thus designers are indifferent about potential future mis-match or feature overkill, staying curious may however seem to be a needless effort because the answer already seems to have been found.

As mentioned previously, if the issues are fundamental (Quality-of-Life, QoL) and the target group(s) more vulnerable the risk of a path-dependency based on first quick success cannot be ignored. Similarly, starting the design all over again if new use-cases come into play is also not desirable if the problems are dire. In practice, steps whether large or small, can only be taken one at a time. In all cases an important question remains: does this happen with at least some strategic intent and acknowledgement of future diversity of requirements? The more one acknowledges the element of inclusiveness, the more poignant this question becomes.

Following this line of reasoning, it starts to become clear that we are in need of next steps in the evolution of design engineering methods to suit this era of *global sustainability-driven scaling*, see Figure 2.3. While still acknowledging the main design characteristics as outlined in 2.2.1, the aim should be to seek to foresee and if possible reduce the technological path-dependency (Berkhout, 2002), lock-in and exclusion effects that dominate current practice. Since systematic variation is both the oldest characteristic and seems to drive the design process whereas the other ones are more consequences, the logical starting point for such a next step is to investigate whether this leading characteristic can be leveraged better to reduce the risks that the aforementioned problem – unwanted path-dependencies due to early uninformed decomposition - occurs. At the same time such a next step should ideally present some guidance to deal with the implications as shown and discussed, unpredictability, loss of control, questions about accountability. In short, these are the consequences that in many managers' eyes jeopardise overall manageability (Sargut and McGrath, 2011), even if they do acknowledge that complex situations have different dynamics (Sargut and McGrath, 2011).

2.2.4 Introducing novelty

2.2.4.1 To design professionals and academics

The result of explorative work is obviously not known beforehand. As referred to in the research question, a form of novelty in the shape of a (valuable) next step in applying systematic variation in design engineering methods is going to be introduced and explored. This implies there might be some resistance from vested interests. This is in a way the paradoxical nature of the academic world: on paper it revolves around introducing something new but as a system it seems to favour confirmation of what we do know even more (Kaufman and Gregoire, 2016). This can of course be observed as far back as human history goes and has been the case for Nobel laureates as well (Campanario, 2009).

How can this insight be used? One of the ways how this risk can be mitigated is by already making very clear that this work should be interpreted as standing “shoulder-to-shoulder” in advancing the field (Kersten et al., 2018b). Secondly, it is precisely because of this notion that novelty in academic research is better framed as an adjacent possibility (Johnson, 2011) than as fully new discovery. In this case indeed the framing as presented so far adheres to this wisdom: the notion that is suggested to be further explored, i.e. the use of systematic variation, does build on earlier work but does – it has to be mentioned – introduce an additional element as well in terms of the place in the design process where this variation is suggested to take place.

2.2.4.2 To junior designers (Master level)

The empirical focus for this thesis-research is strongly based on design assignments of Master-level IDE (Industrial Design Engineering) students. This choice is further explained in section 2.3 (Research approach), but is taken as a given for the purposes of this section. These Master-level students are design-engineering-professionals-to-be with several years of nascent experience, a decent base level of design knowledge and openness to consider to enhance their arsenal of design approaches, methods and tools, whereas expert designers might be hesitant to try novel approaches. Nevertheless, introducing a form of novelty to Master-level students, or junior designers as they might be called, has its own challenges.

The dynamics of introducing something new to students are different than with seasoned professionals but the main questions still revolve around the challenge of what is required to stimulate adoption. As an application of the statement that to ease the adoption innovation needs to be “adjacent” (Johnson, 2011) or as little different as possible from what people know (Hartmann and Linn, 2008), in this case we might wonder what the level and type of guidance for students would need to be. For example a logical question is whether they would require a detailed manual on how to interpret and apply the possible next steps in design engineering methods.

Providing details, even instruction-level style, has potential benefits but also many possible drawbacks, especially in light of "the learning experience". It is not evident upfront which should weigh heavier. Some drawbacks of detailed instructions (on activity-level) are that the inquisitiveness of students, the will to try, experiment and make something their own is dampened. That hurts the richness of the learning experience. Benefits may include to reduce the risk of confusion, uncertainty and in the worst case paralysis, or alternatively, unintended use of the (new part of a) design approach. We can already see a very interesting discussion looming whether "unintended use" of anything is bad per se, and similar considerations for the other drawbacks: if these occur, how bad is that and why?

A point that this thesis is expected to gather insights on is the type, degree and level of guidance that (junior) design engineers, and possibly non-design professionals require, to adopt novelty in terms of design engineering methods.

2.2.5 Exploration areas for this thesis

Based on the discussion in this chapter, and as an inductive summary rather than conclusion, the list below contains areas that deserve more thorough exploration in the form of an extensive literature review in the next chapter. This selection is an important step to identify the current state of knowledge of the most relevant topics that emerge from the exploration thus far and together represent the integral theme ***systematic approaches in design engineering, in the context of an increasingly globalised and sustainability oriented society.***

These areas for further investigation should be considered as plausible directions following the preceding explorations. There is no 'mathematical' guarantee that these are the only or proven best areas to explore, but doing so will certainly provide relevant insights to feed into next steps. The suggested research areas for extensive literature research are clustered according to the main angles as presented in section 2.1.3:

Design engineering arsenal:

- How has the aspect of <u>systematic design engineering approaches</u> evolved so far?
- What might <u>logical next steps</u> be for such approaches, in the face of ever <u>increasing complexity</u>?
- Are there areas in the <u>design engineering lexicon</u> that might benefit from more shared understanding to increase acceptance for such steps?

Empirical framing:

- What might such changes imply for business practitioners and managers in terms of alignment with or divergence from current practices?
- How might such steps (positively) influence strategies to achieve large-scale sustainable impact and inclusiveness?
- What might such changes imply for design engineering education in terms of knowledge and/or skills that are to be taught or facilitated in a way that these changes are accepted?

2.3 Research approach and methods

As the main research question (2.1.3) and the end of the previous section implies, this thesis focuses on the by now emerging question what a next step in the evolution of design engineering approaches could look like against the backdrop of complex design challenges, in particular related to the characteristic of systematic variation. This next step is intended to prevent or severely reduce occurrence of the identified problem, i.e., *lack of scalability of products that aim to address complex design challenges, where the complexity amongst others is represented by potential but underutilised interrelations between different contexts in which the challenge occurs.* As discussed, the primary cases for which this question is relevant take place in emerging markets, and are related to quality-of-life issues. The question might still be relevant for other cases as well. This focus is guided by the expected level of societal relevance and thereby meaningful results.

This type of research promises to be highly exploratory, i.e., there are no ready-to-use or developed hypotheses that can state an expected and extensively substantiated relationship between two or more theories. Neither does the empirical setting for this research itself allow for *testing* any hypothesis by using large data sets referring to comparable situations. For these clear reasons, the main approach is inductive. The aim is to discover whether promising arguments exist that suggest whether additions to design engineering theory and practice are warranted. These additions can then be investigated or elaborated further in follow-up research.

2.3.1 Overall approach

An overall approach that is suitable for this type of research and fits the researcher who is in the lead requires an intentional mix of methods, which are described below. These represent a harmonious mix based on the insight that design engineering is a combination of Science (Knowing, thinking) and Art (Doing, materialisation) and constantly moves from one to the other and back.

The choice for the main methods in the research approach is therefore two-fold: 1. Because of the characteristics of the PhD-researcher (experienced, inquisitive, strong in a combinatorial sense) and the open nature of the topic, the reflective practitioner approach (Schön, 1984) makes most sense, 2. Because of the necessity to include real-life insights in addition to only sources from theory, case studies ("cases") are used.

The general academic attitude fuelling this thesis is one of inquisitiveness, the expectation to find, discuss and reflect on emerging (qualitative) patterns that are opening up instead of closing down the search space, and suggest additions to current thinking instead of testing the validity of specific current thinking (hypotheses). In short, the required process for this research is characterised by being inductive and should be driven by creative inquiry (Montuori, 2005, Montuori, 2012), possibly more so than the desire to find (final) answers. Consistent with that attitude the research will not make use of statistical analysis, which typically aims at finding quantitative levels of certainty about a very small part of reality. When sensible and feasible, the use of numbers as part of the collected data and insights might support the identification and discussion of qualitative patterns. One foreseeable example of including numbers when identifying patterns is the use of Likert-scale questions when collecting opinions from a medium-size group of design engineers.

The steps as can be distinguished in the overall approach for this research are as follows, including where in the thesis these steps are taken that are further elaborated upon in the next sub-sections:

1. Excavating literature based on reflection which academic areas are relevant to include (sections 3.1 – 3.5)
2. Based on extant literature, experience and discussion with design experts, highlight key defined constructs that have emerged from the literature research (section 3.6.1) and inductively develop *propositions* on topic areas that deserve empirical exploration (section 3.6.2).
3. Create real-life *insights* in relation to the propositions by using cases and reflecting on available written and oral information in relation to these cases (chapter 4, section 4.3)
4. *Identify and discuss* the overarching patterns in terms of the *extent* to which the insights from the cases support or oppose the propositions (section 5.1). These represent a first glance, not a quantitative analysis.
5. *Discuss and reflect on these patterns* through the *in-depth lens of the literature* and suggest what these patterns tell us (section 5.2 – 5.4)
6. *After answering the Main Research Question* (MRQ), *suggest next steps* based on these discussions in terms of further (academic) conceptualisation and implications in practice (chapter 6).

The use of the two main methods in light of these steps is discussed in the next sub-sections.

2.3.2 Reflective Practitioner approach (all, especially step 1, 2, 5 and 6)

The general attitude for this thesis revolves around the reflective practitioner approach (Schön, 1984). The main elements that drive such an approach are a deep knowledge of the topic at hand and, as a consequence of this deep knowledge and active attitude by the researcher, the unavoidable absence of full objectivity. In reality that objectivity, in particular in case of qualitative research, is often an illusion anyway and it may be more productive to think in terms of intersubjective reality. To let the research result in valid and academically acceptable conclusions, this lack of objectivity can be mitigated through various measures including the use of multiple perspectives and using diverse sounding boards as input for tentative conclusions and next steps.

To that effect, figure 2.4 depicts how the reflection between the researcher and the relevant research-environment (design experts with academic and/or practical orientation, academics in other fields than design engineering, students, principals) takes place throughout the entire process from reflecting on the identified problem onwards. A variety of settings for these interactions were used, in particular in-depth discussions with design experts inside and outside the faculty, meetings with and observations of students during the execution of and reflection on their assignments, presentations, discussions during conferences, and discussing draft papers with peer-reviewers for publications.

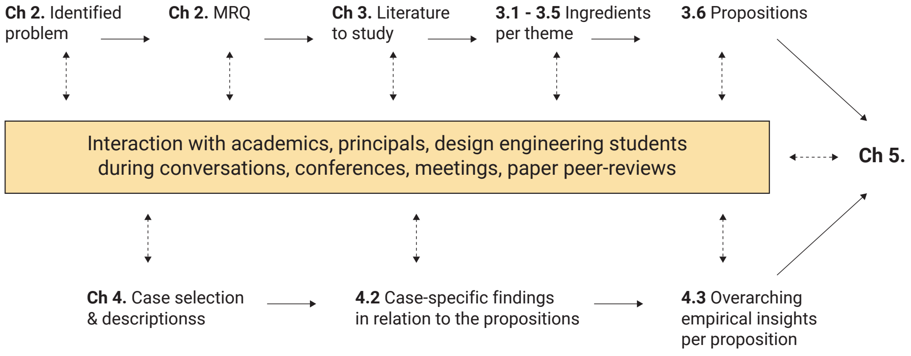


Figure 2.4 Continuous reflection as backbone of the research process

The necessity of this approach is driven by the expectation that sensing (qualitative) patterns is more relevant than striving for statistical certainty (Schön, 1984). While seemingly more value-dependent, the notion of sensing patterns also reflects reality that contemporary academics, possibly except for the hard core natural sciences, acknowledges that actual reality is richer than one provable and universally applicable truth. The subject matter is not suitable for a deductive approach, as explained in sections 2.1.3 and the introduction of 2.3, However, it can be expected that the extensive excavation of literature provides a good enough basis to formulate *propositions* that can subsequently be elaborated upon by empirical cases. This is a suitable basis to discuss the plausibility of the propositions, which will provide directions for elaboration through further inductive research.

When applied to the design domain we can see that the design profession is no longer simply characterised by meeting or defining clear-cut problems and solving them with one best solution. Instead, many situations that design engineers have to face have high degrees of uncertainty, instability and value conflict in them, so the way in which design engineers should approach these situations is less through an analytical and more through an intuitive, reflective. inductive lens (Schön, 1984). This allows more room for surprise and possible confusion but also allows space for a better understanding regarding consequences of actions as part of the process of discovering a more desirable future. As (Schön and Wiggins, 1992) explain by referring back to both the bounded rationality-paradigm (Simon, 1969) as well as the management challenges: whereas humans may have limited ability to deal with the long-term uncertainty inherent in complexity, by actively reflecting on the observable consequences of actions and steps, they *can* accelerate that understanding. In other words, when basing increased insight on actual observation (seeing) of actions, designers will be able to translate this seeing into knowing which actions might lead to more and less desirable directions. We can again refer back to Leonardo da Vinci who extensively relied on observations, testing and (re)setting theories and hence expectations (Isaacson, 2017).

Although translation into action is sometimes labelled as necessarily opportunistic (Lindstrom, 1959) and guided by “taking whatever action is possible at the moment” (Norman and Stappers, 2015) this type of guidance might not be the most suitable *design* strategy. After all if not in the design domain, where else could one find a good sense of direction, intent, and longer term horizon? The word “design” even if taken in the lightest possible dose does imply a sense of intent: the two terms – “by design” and “intentional” – are merely synonyms. In other words, by definition only one step at a time can be taken, and better or worse next steps will emerge from each one. It seems perfectly reasonable to combine the two. Moving ahead ‘one step at a time’ is the only possible way but how much effort has been put into imagining the more general direction of where that step is intended to lead to? There is much to be said in favour of having in mind a longer term vision and sense of direction, i.e., intent, with emerging results helping to set a more concrete course. Lack of either, i.e., no vision or no actionable next step in the direction of what the vision represents, is a likely recipe for failure. Both are required and framing should therefore take care of not discarding either, even if the latter is unintended.

Questions in a research process like proposed are more open and inquisitive and success is less defined by arriving at the one perfect answer or "solution". Understanding the actual situations and creatively contemplating what the problem at hand in fact is, is becoming increasingly valuable compared with following a structured process to solve a clearly defined problem. The design profession is sometimes, even proudly, described as being perfectly positioned as problem solving discipline (Buchanan, 1992, Dunne and Martin, 2006, Brown, 2008). It may however be doubted whether this reflects the most relevant mindset in light of the aforementioned increase in complexity and thereby "unsolvable problems" and wicked ill-defined, perhaps even ill-definable, problems (Rittel and Webber, 1973). Changing ill-defined problems into well-defined ones is not a topics that is going to be addressed in this thesis. Moreover, when mentally focusing on problem solving as ultimate aim, necessary attention may be taken away from proper problem setting (Schön, 1984). This in most cases results in "searching within a problem space" (Schön and Wiggins, 1992), which foregoes on the more reflective question how that problem space was constructed in the first place. More attention for the process of problem setting as opposed to solution finding very much corresponds with the statements in section 2.1: a current response to manage the complexity of a design challenge is to define a narrow problem scope early on, meaning that the search for 'solutions' including all creativity that comes with it, is focused on that intentionally limited scope, *the* way forward.

Designers in particular however might increasingly have to rely on improvisation to deal with a wide array of situations coming their way. Improvisation however is rooted in mastering the basics to be able to vary elements and reframe a challenge. Complexity is not suitable to attack with blueprints, as appealing as that may seem. This can also be judged by the fact that standardised tools that claim to do exactly that are becoming popular (Backx et al., 2017, Brown, 2009). This does not mean however that there cannot be some level of intent, based on mastering the aforementioned basics. In other words: to fight complexity, instead of relying too much on tools that promise to simplify your challenge or decompose it in one particular way, rather it may be called for to accept the complexity as it is and find honour in combining, recombining and disconnecting known building blocks. In that sense, design may be seen as a craft to bring about change by conducting a metamorphosis of components into a solution (Sennett, 2008).The key to do this in complex situations does not lie in adding resources and supplying tools to execute a huge task, these are the response strategies when a challenge is complicated. In case of complexity, the key is to *connect dots* and by allowing that to happen see new patterns emerge (Wheatley, 1998).

This is the core attitude that is required for this process: recognising patterns, including “known knowns” but also “known unknowns” (Snowden and Boone, 2007) when they occur, and by means of continuous reflection as depicted in Figure 2.4, being able to vary approaches and expectations based on reality, while still working from a basic intent. By taking very little as a given, acknowledging the possibility of “unknown unknowns” (Snowden and Boone, 2007) and allowing active reflection to take a front seat, chances are much higher that the researcher can figure out what makes sense to do and how that holds up in practice instead of focusing on what was planned or what the structured process prescribes as the solution.

This does not imply that planning or preparation is useless. After all, “A plan is useless, planning is indispensable” (D. Eisenhower), and “Chance favours the prepared mind” (L. Pasteur). In practice this means that meeting with unexpected or initially confounding results are not a sign of failure but an invitation to reflect on the reasons behind that unexpected outcome, as step towards deciding what should change: the expectation, the method or the outcome. In this way the whole process is generative and discursive: all necessary steps are taken but the fact that they need to feed each other and the reported sequence is logical is more important than the exact order in which this occurs in reality. Unexpected occurrences should be considered to provide a reason to be more inquisitive, they should not be the end point of the process of inquiry. The continuous reflection in practice results in a more systemic approach than analytical validation of hypotheses and binarily accepting or rejecting these.

2.3.3. Case research (step 3)

Referring to (Yin, 2017) with regards to case (study) research, there are multiple arguments to support the choice to make use of case studies, or simply called cases, in this thesis:

- The *propositions* as *inductively derived from extant theory*. The type of exploration, including few historical data for comparison, does not lend itself for large-scale statistical deductive analysis, which turns using cases into a logical choice.
- The *landscape* related to the observed phenomenon is *dispersed*, so there are too many variables for any meaningful large-scale statistical analysis in the first place. Instead, using *contemporary case studies that represent real-life diversity* offers a productive environment for the intended inductive exploration. The reflection on these empirical data does not have to result in definite conclusions on the generalisability of the results.
- The *researcher has limited control* over the events that are assessed, i.e., the events are part of a contemporary phenomenon within a real-life context, not a lab-setting. This implies the observations are to

some extent subjective by default, but are likely to create a deeper *understanding* of the subject matter. By regularly discussing the results with others, the findings can be used to discuss the possible – intersubjective - *meaning* of the information as opposed to one single objective truth.

- The main *research angle is qualitative, the aim is to identify and discuss patterns* in relation to the propositions. To make sure the input for this is rich, it is not sufficient to just rely on information from academic publications. The empirical information, structured by means of how it relates to these theory-based propositions, is intended to kickstart a rich reflection and discussion into the *meaning* of the findings, not to close discussion in search for one definitive answer. If the rich results from the cases do not correspond with the expectations as stated in the propositions, this is food for relevant academic discussion as well. I.e., if propositions are not supported, the cases have not failed, they just provided even more reason for deeper reflection. This is consistent with the reflective practitioner approach.

The considerations for the types of real-life situations and identifying which of these are suitable to serve as cases for this thesis are discussed in chapter 4.

As announced earlier, the search space for the real-life situations from which cases are going to be selected was focused on assignments during Master-level education, in particular the IDE-faculty of Delft University of Technology. Besides the remarks on the quality of these students (see 2.2.4.2), this choice was a practical necessity, thanks to the expected access to high-quality information that is feasible when working with students and the hesitant first reactions from expert designers in commercial settings. It is however important to emphasise that expert designers were actively involved in the research and cases, in different ways: the academic supervisors (some with dual functiona in academics and practice), the supervisors employed at the principals, and a variety of experts during conversations at conferences and public events, all ensured that the cases as presented here cannot be considered to be just academic exercises. More details on the process of identifying relevant real-life situations, and selecting cases for in-depth inclusion in this thesis are presented in chapter 4.

2.3.4 Comparing and discussing (steps 4 and 5)

The ‘exciting’ part of the thesis consists of comparing the propositions and key defined constructs that result from the literature research (section 3.6) with the findings, and eventually the overarching insights that are provided by the empirical cases (chapter 4). By having as few as possible preconceived expectations of the outcome of this comparison, that actual step in the inductive process will remain one to look forward to.

This does however require a truly reflective and open mindset. The topic areas that are included in the propositions represent some level of expectation, but if the empirical insights suggest that there could or should be different (research) directions to pursue, then the research has far from failed, as mentioned above. Likewise, if expectations *are* largely met, i.e. if the empirical insights would clearly support one or more propositions, that would not imply the end of the investigation, but could be an invitation to devise further research settings that put the empirically-based conclusions with regards to these propositions to a stronger test. This thesis reflects the start of this journey rather than the end. The empirical insights may also neither clearly support nor oppose the propositions. This in fact is a likely result in this stage of exploration. All in all the main aim is to use the insights in relation to the propositions to help guide the process of better grasping the subject-matter.

Because of the highly qualitative nature of the topic, and also of the expected empirical data, the focus is not on making this data comparable through quantification or similar, but by describing and discussing the case-specific findings, through the lens of the propositions. That introduces a level of comparability. This allows overarching insights per proposition to be constructed, composed of the findings in each case related to that proposition. The step from case results to proposition-relevant-findings is to be done by the researcher. The main general safeguard that this occurs in a responsible and non-arbitrary manner is the use of continuous reflection and interaction with a variety of stakeholders, as illustrated in figure 2.4. This interaction is organised amongst others in the form of in-depth discussions between the researcher and design experts regarding the choices that are proposed by the researcher for the translation from case results into findings per proposition. The same goes for the next step of composing the overarching empirical insights from the case-specific findings. The construction of these insights does facilitate final reflection on and discussion of overarching patterns by the researcher that takes place in chapter 5. More specific comments on how sound, non-arbitrary and non-biased choices were made in each step of the process are included in each chapter that represents these steps.

2.3.5 Suggesting next steps

Since the results of the previous steps are wholly unpredictable at this point, for now it is only possible to state that any outcome of the research can provide arguments for next steps.

As mentioned above, if the patterns from the empirical insights (result of chapter 4) suggest that the topic areas as expressed in the propositions (result of chapter 3) need further rethinking, it can mean different things. In general a logical next step would then be to reconsider (framing of) expectations as input for next steps.

Likewise, if propositions are largely supported by the empirical insights, or point strongly in the same direction, next steps could include more ambitious research. That research might be based on more strongly formulated propositions, or might suggest more 'evidence-seeking' approaches. Alternatively, with the increased understanding that this thesis aims to offer, reframing of future research areas might be possible. At the very least a further conceptualisation can be expected.

This is the core of the reflective approach: to not work with foregone conclusions or hidden expectations about results, but let the appropriate attitude towards the ex-ante propositions evolve in the face of the emerging insights and patterns, before deciding how to move forward.

2.4 Reading Guide

With the run-up to the thesis process and the design of that actual process clarified in the first two chapters, this section contains a brief navigation to the rest of the thesis.

Chapter 3 excavates the literature on a number of selected topics. These are listed in section 2.2.5 but are introduced at the start of the chapter as a reminder. This excavation starts with the design engineering domain, but is not be limited to it. The role of design engineering in contemporary society touches on other fields of interest. While not covering the entire knowledge-landscape it is certainly suitably broad for the purpose of this thesis.

The extensive elaboration of the chosen themes is needed to have a full understanding of the most relevant historical developments and trends. Each section ends with an inductive summary of ingredients from that section, which at the end of chapter 3, upon reflection with primarily academic design experts (as shown earlier in figure 2.4), are combined into a set of propositions together with a brief summary of main key defined constructs. The latter term means that these constructs are neither purely theoretical nor purely operational but represent the conceptual link between both, and this thesis intends to offer an argued, defined, version of that link for a small number of defined terms, the ones are to be considered as pivotal to this research. As part of the literature research, a visual conceptualisation (version 1.0) of the design approach is offered that is to take centre-stage in the remainder of this thesis in section 3.1.6. The visualisation is presented in the same style as figure 2.2 (section 2.2.1), i.e. a regular design engineering approach.

Chapter 4 contains the criteria, selection process, description and relevant results of the cases. All cases are selected from a longlist of real-life situations. The selection of cases from this longlist is based on the access to high-quality information and thereby the likelihood that these cases contribute to providing valuable empirical insights on one or more of the propositions, not on whether they will support these propositions. The selection process is agnostic in that respect. The results of the reflection on the cases are first presented in the form of case-specific findings in relation to the propositions that are listed in section 3.6. These case-specific findings are then upon further reflection and in-depth discussion with relevant stakeholders, as indicated in figure 2.4, clustered into overarching numbered empirical insights per proposition in section 4.3.

Chapter 5 then starts with interpretation of the results of the cases as compared to the propositions. This first results in identifying overarching patterns with regards to the question *to which extent* the empirical insights support or oppose the propositions or mainly point at evolving insights with regards to the proposition-topics. This result is then scrutinised in-depth through the lens of academic literature from chapters 2 and 3 and additional sources where the results provide reasons to do so. This discussion then feeds into reflecting on the initial conceptualisation and visual in chapter 3 (presented in section 3.1.6) and suggests how this conceptualisation might be improved towards a version 2.0. This reflection is the final bridge to suggestions how this research might provide added value to existing literature and thinking about design engineering and be used as basis for new research efforts.

Chapter 6 pulls the thesis together by translating the discussion and reflection in chapter 5 to the overall conclusions in terms of the research question and the main research angles, a brief discussion of limitations, methodological considerations and suggesting next steps that are relevant for research, practitioners and design engineering education.

Chapter 3

Chapter 3: The state of academic literature

This chapter describes and explores the main extant literature and provides a first deeper discussion based on that literature on the five themes that are introduced immediately below this paragraph, and are underlined for overview and clarity's sake. Each of these underlined themes is then covered in a separate section (3.1 - 3.5). This exploration results in a tentative list of inductively created ingredients per theme, highlighted at the end of each section. At the end of the chapter (3.6) these ingredients are taken one inductive level further to compose propositions. Some of these propositions refer to one theme, others combine themes. Together these propositions represent the framework for reflecting on the empirical part of this research.

As this chapter demonstrates, literature has been studied from domains as varied as business and management, anthropology, economics, international development, psychology, architecture, innovation. In short, the research is conducted starting from the design engineering domain, with openness to be enriched by many other domains.

As is clear from the previous chapters, a pivotal theme is the set of developments with regards to systemic and systematic design engineering methods. The chapter therefore starts with a historical overview of the design engineering field, in particular pertaining to evolution of systematic design methods (3.1). This is followed by discussing the – mostly recent - history of increasing globalisation (3.2), and exploring the consequences of where we stand now from different angles (product development, management, financial) in 3.3. The consequences are excavated slightly deeper in section 3.4, from the perspective of large-scale issues with different contextual manifestations. To close off the literature review, section 3.5 explicitly captures the phenomenon that is the actual red thread in all of these developments: complexity. The most relevant aspects that were touched upon in the chapter are brought together under this overarching and connecting theme. The interconnectedness of the themes within this chapter and between chapters 2 and 3 makes partial redundancy on the one hand impossible to avoid. At the same time it in fact demonstrates that such redundancy is, certainly in the context of complexity "a feature, not a bug": even when approached from different angles, the discussions in this chapter logically touch similar topics, and thus the "web of interconnections that weaves complexity" (Montuori, 2011) becomes reality.

It serves to keep in mind when reading this chapter and in particular when contemplating the formulation of the ingredients and eventually the propositions, that this is all the intentional result of the reflective practitioner approach, as discussed in section 2.3.2. The inherent subjectivity to move from literature to ingredients to propositions is mitigated by the continuous and intentional wide diversity of interactions by the researcher with relevant stakeholders which can be considered as a cultivation process to reach the eventual result. For this chapter, the main results of these interactions are visible in the form of the ingredients at the end of each section. These are the result of extensive deliberation with academic design experts, in which opinions were compared and incorporated as to what constitutes the main elements of each particular section. By revealing the results of that deliberation, i.e., the ingredients, the gap between the many pieces of knowledge obtained from literature and the eventual propositions is decreased and thereby the transparency of the process as a whole somewhat increased. Even earlier in the process, the extensive excavation of literature in each section, has been thoroughly discussed with design experts to ensure that the choice of sources and their interpretation possessed a good extent of subject-relevance.

Besides the propositions that offer the main navigation to structure and assess the results of the empirical research, as was announced in section 2.1.3 and 2.4, this chapter also provides the basis to present key defined constructs for this research in section 3.6.1. The process to establish, select and describe empirical cases in a sound and unbiased manner follows in chapter 4.

3.1 An overview of the evolution in systematic design engineering

This section discusses the evolution of methods and paradigms that have shaped the nature of design engineering throughout the centuries. As follows logically from the preceding chapters, this discussion in particular includes the different ways in which the methods and lines of thinking represent a systematic mindset. The historical journey is mostly chronological, in the later sub-sections one can see more branching off into different streams rather than pure adherence to a chronological order. Expert design engineering readers will recognise that many of the authors were mentioned in the seminal and still core work on systematic design engineering (Beitz and Pahl, 1992). This is complemented with some insights that they could not have had in their time. This section is mostly descriptive which includes several of their observations. The section is not intended to provide an original contribution to the field, it primarily conveys an understanding of the developments in the field of (systematic) design engineering and where these developments have brought us.

The visual representation of the evolution of design engineering drivers was shown in Figure 2.2 in chapter 2. It is not to be seen as a rigid model but with this figure in mind the transition between different phases of the evolution of design engineering as described below might be followed a bit better.

3.1.1 From Leonardo until WWI

As a starting point for this historical overview it is appropriate to look at Leonardo da Vinci. He is probably the first documented 'designer' to move away from a traditional purely artistic or artisanal approach to structured design, including engineering. Instead he developed a discovery-driven mindset for himself and the (junior) artist-designers he worked with by perfecting systematic variation in his observations whether as part of an art-project or an engineering-endeavour, including proposing possible solutions to a given problem (Isaacson, 2017), which for example can be seen when his work is exposed to ultraviolet light (Roberts and Pedretti, 1977). His approach combined the previous focus on arts and crafts with a more structured one that is usually more associated with science. This synergy may very well be a reason he is considered as one of the greatest in a variety of fields, including the arts itself. He also helped to revolutionise many practical fields, including engineering, water management and understanding of anatomical processes (Isaacson, 2017).

Until the start of the early industrial revolution and the rise of mechanisation that came with it only very few followed his example. This mechanisation implied a necessity for focus on physical properties (Redtenbacher, 1852). The "father of kinematics" Franz Reuleaux, labelled as such by (Moon, 2002), and Moll developed this further but also asserted that the relative importance of different properties in case of conflicts was to be addressed at discretion and intelligence of the designer (Moll and Reuleaux, 1854). Others, (von Bach, 1881) and (Riedler, 1913), asserted that materials, production methods and strength are equally important and interdependent.

3.1.2 Refinement of systematic design engineering (WWI – 1965)

Despite the first emerging thoughts on functional and systematic properties that designers could consider, the main view on design by the turn of the century (1900) revolved around design as a discipline occupied with shaping forms and producing artefacts. This dominant view was still present even a century later (Nelson and Stolterman, 2003, Latour, 2009).

In an ironic twist of fate, the two world wars (WWI and WWII) have put design engineering at centre stage. Driven by the industrial revolution, the combination of an ability for design innovation and a capacity to manufacture new innovations at scale has to a very large extent determined the course of victory in both cases. This statement is related to the historical observation that the war-settings ensured that an order of magnitude of funding was available that would otherwise not have been the case. In hindsight this has strongly influenced the overall dynamics of the evolution of (systematic) design engineering, in and after that period.

After WWI (Rotscher, 1927) stipulated his more refined vision on the essential characteristics of design, being a specified purpose combined with effective load paths and efficient assembly and manufacturing. Throughout the process calculations go from rough (preliminary layout) to precise (detailed design), to support decision making. This was built upon on (Laudien, 1931) by stressing not to over-specify, fulfil only the specifically required demands, save by simplification and construct economically. All this was in particular applied to rigid connections in designs.

One of the first to develop design-related thinking on systematic approaches was (Erkens, 1928) who suggested to apply constant testing and evaluation and balancing the set of different demands until a working design emerges. The views of Erkens were refined (Wögerbauer, 1942) by putting emphasis on the division of the main task in sub-tasks which can all be further divided in operational and implementation activities. The interrelations between the constraints within these tasks should be considered, but he did not offer a systematic way to do this. The designers should start from an intuitive overall design and then vary comprehensively with respect to form, materials and manufacturing method. Testing and evaluating brings down the number of potential solutions to an optimum one, with costs being a crucial criterion.

Around WWII the main dominant insights were that no reliable methods existed to represent abstract ideas, and the dominant view was still that design was merely an art form, rather than a technical activity. These impeding factors did not stimulate the development of systematic design on a large scale.

From WWII onwards a succession of pioneers challenged that status quo. This started with promoting successive approximations (Kesserling, 1951), a practice started in WWII, constructing a technical composition based on technical and economic criteria. This mainly applied to optimisation of parts and simple artefacts: form design, in large part based on mathematical calculations. Emphasis was put on starting from working principles (Tschochner, 1954), which result in choice of materials and form, leading to a design with chosen dimensions. In parallel work was pursued based on the option to start with a scale lay-out, then working on developing parts in parallel, followed by systematic variation of possible solutions from these parts eventually resulting in a formal selection of the optimum (Niemann, 1950). This is one of the more explicit forms of systematic design.

The factors working principle, materials, manufacture and form design were used by (Matousek, 1957), resulting in an overall working plan. If the costs turn out to be too high, all four factors can be reiterated. The relevance of costs to make choices and optimise design corresponds with the relevance of this aspect (Wögerbauer, 1942).

Finally, another direction was being mostly occupied with form design (Leyer, 1963). He suggested to start with an idea/ invention/ fact, which results in a working principle, followed by the design phase and implementation. In the design phase the embodiment is the core of the process, i.e. the layout and form design based on calculations. In his method the *working principle* is the absolute core of good design.

By then upcoming sectors reflected the necessity of more precision as experienced in for example power transformation and electromagnetic engineering. This meant that at the same time systematic methods became essential and complexity was strongly increasing.

3.1.3 Towards design in a societal context (1965 – 1980)

Hansen and the Ilmenau school started with systematic engineering in the early 1950s, culminating 10 years later (Hansen, 1965). They asserted the importance to focus on the crux of the task which is similar across situations. This should then be followed by engaging in purposeful combinations aimed at identifying and reducing shortcomings to select the version with the fewest shortcomings, which can then be documented for practical evaluation and implementation. He later published work that contained the more theoretical foundation of design (Hansen, 1974) as opposed to practical rules.

Arguably the largest impact in the field of systematic design was the approach to consider the purpose/ function as the core of design (Rodenacker, 1976). He looked upon designing as in essence being a transformation of information from abstract to concrete and a reversal of physical experiments. He uses eight rules to result in a series of design steps, as shown in (Beitz and Pahl, 1992). The core function structure and thereby logical relationships are based on separation, connection and (e.g. for purpose of energy flow) channelling. For him, identifying and eliminating disturbing factors in relation to the function was essential. In his view the main factor for systematic design is determining the underlying physical processes. By understanding these it becomes feasible to search for new applications of known physical effects as basis for original solutions.

Roth had (also) divided the design process in different phases with specified steps with room for iteration if the results of the steps require this (Roth, 1968). As overarching characterisation, he refers to his whole process as being an algorithmic selection (Roth, 1971). The information for individual steps is chosen from catalogues, implying that compiling these catalogues is very important. This might be best achieved by doing the compilation process in a systematic manner. This development is one that we might recognise as a form of creating richness in the design space, getting better informed before making decisions. This notion is going to be discussed more elaborately later, in particular in section 3.5.

Koller also breaks down the design process in a number of steps with emphasis on elementary physical connections (Koller, 1973, Koller, 1976). The aim is to be able to use algorithms for design choices to optimise a design based on known requirements, and thus be able to automate the process of making (= calculating) these choices. In order to achieve that, clear rules must be established. Complex technical processes thus are reduced to a distinct number of physical functions. Putting physical and logical relationships together based on basic operations is basically the synthesis that a designer should be concerned with. This very function-oriented view of design becomes more qualitative by translating it, again using clear rules, into the required form and shape. There is plenty of room for variation in this approach, e.g. trying out different materials when translating the functional into the form design, as long as the options can be calculated and compared.

3.1.4 Modern-day approaches related to systematic design

The writings from Pahl and Beitz as referred to have from the 1980s and 1990s onwards been the dominant force in design engineering literature and had a strong influence on method development by others, e.g. (Roozenburg and Eekels, 1995), (Buijs, 2012). Still, during the last decades of the 20th century, more flavours of design engineering methods did come into use as well ,which in some form or the other used a systematic mindset. Roughly these flavours represent the 3rd wave that was mentioned in section 2.2.2, i.e., the wave that represents the more explicit consideration of design engineering in a real, human-driven, societal context. As mentioned before, several of these ‘flavours’ of methods, approaches and tools for (parts of the) design engineering process are collected in the Delft Design Guide (Boeijen et al., 2014, Van Boeijen et al., 2020, rev. ed.). They are on purpose here referred to as a whole because singling out any specific element of that guide would immediately provoke questions why that one and not other ones.

As one, though not only, pivotal acceleration of this wave, the parallel notions of the intertwining of technological and social aspects and the concept of bounded rationality (Simon, 1969) started to gain traction. The latter was discussed in chapter 2 as well.

3.1.4.1 Systems approach

If one considers a technical artefact to be a system, it is a small step to apply systems theory (Ackoff, 1971, Ackoff, 1973, Meadows, 1997, Meadows, 2002) to design. A systems approach proposes fixed steps each with analysis and synthesis, to address (complex) issues: 1. Gathering of information on the system under consideration, meaning there is consensus what the system is, resulting in clear problem formulation, 2. Programme of requirements stating the goal of the artefact/ solution which is the leading criterion for eventual assessment; variants for this eventual solution can be constructed from several sub-solutions so the best optimum can be found. This might be called *variation within the design task*, 3. Documentation to support the implementation of the optimum (Beitz and Pahl, 1992).

This approach is mostly used for function-oriented synthesis. If a known or developed concept is the basis, all combinations of known or selected inputs, outputs and their links can be optimised mathematically to satisfy the demands of the problem. Such systems models governed by mathematical rules are amongst others established for signal-processing equipment. Richter and Findeisen further developed and applied this method for optimising dynamic systems (Findeisen, 1974).

In case the functions, demands, connections and so on are less clear and it is therefore less easy to put together a model governed by mathematical rules, this approach may not be the most appropriate one to use. This is likely one of the reasons that introduction of system modelling in the design domain was not necessarily met with immediate enthusiasm (Collopy, 2009), in part because it was done in a relatively top-down fashion (Sevaldson, 2017b). Designers, even design engineers mostly seem to take pride in their profession in terms of its generative quality as opposed to merely mathematically driven optimisations. Another way of putting it is to say that design challenges with different conflicting requirements will need to be *satisficed*, instead of optimised. This may involve qualitative reasoning as well. Satisficing is necessary in any situation with three or more variables (i.e. requirements). While computers may in a *computational sense*, be able to calculate optimums with three or more variables, that does not necessarily result in real-life meaningful results. People on the other hand, are limited by bounded rationality (Simon, 1969) and to take meaningful decisions that combine different requirements, they need to conceive of, i.e. (mentally) visualise, the results of the process. The limitations can also be observed in time. In principle if time is not a condition the longer we think and try, a design can always be improved and currently unforeseen circumstances can be included in our deliberations, which might reduce the risk of setting in motion irreversible negative consequences (Rittel and Webber, 1973). In practice of course there is no infinite supply of time and to some extent this is a good thing because it does in fact “force to deliver”. The key question is of course how the elements of time allowed and achieving a real-life result can be brought into harmony.

3.1.4.2 Design as learning process

In addition to the description of discursiveness in chapter 2, other schools of thought stipulate that a discursive method, i.e. non-linear and with unspecified order of achieving a result but with ability to report on that result in a structured and responsible way, by itself is inadequate and cannot satisfy the designer; therefore automatic control techniques with constant feedback are required. (Wächtler, 1967, Wächtler, 1969) states that "creative design is the most complex form of the learning process", involving not only small quantitative changes at constant quality (rules) but also changes in the quality itself. Similar thoughts have later been popularised under the terms single and double loop learning (Argyris, 1976, Argyris, 1977). Importantly, there is an explicit relation with the environment, which is the source of the problem as well as recipient of the solution. While still in idea-phase, that solution resides in the designer's learning system and continuous comparison with the requirements precedes decisions to move on and eventually 'give the solution back' to the environment where the demands came from. The decision point is reached when the discrepancies between requirements and reality have been reduced to an acceptable minimum (Beitz and Pahl, 1992). The design learning system and environment are not isolated, they are interacting throughout the process (active environment) or the environment merely provides information on demand (passive). In the former case the environment can be said to co-discover the solution.

According to this approach the level of information content needs to be such that the design process can be optimised relative to the overall purpose as stated in the design task. The learning process governs this mechanism until that point is reached (Beitz and Pahl, 1992). Methods thus tend to rely on breakdown in functional building blocks and then composing solutions by solving the problems within these building blocks, and systematically varying the combinations to come to the optimum overall solution, for example by using morphological charts. In complexity-terms we would rather not talk in terms of solutions but more in terms of ways forward, since there are no solutions to a complex problem and certainly not optimal ones (Rittel and Webber, 1973). While such complexity-considerations are far from new, it is not evident that design engineering as a domain, with a focus on coming up with concrete products, can automatically work with this notion of "no solutions".

3.1.4.3 Design Thinking

This approach has some connotation both with the words systematic (i.e. structured) as systemic (i.e. treating the scope as a (large) system with many different interdependent components). It has strong champions (Dunne and Martin, 2006, Brown, 2008) but has also been subject to more critical reflections (Korn and Silverman, 2012) and analysis (Johansson-Sköldberg et al., 2013). In its core it is a problem solving method with concrete, systematic steps, with explicit attention for the perspective of a targeted user-group and deep involvement of that group in scoping the problem and iteratively testing the developed solution. So much has been written about it, that a concise inclusion here would have been difficult, were it not for a recent meta-study on these different views with regards to design thinking (Camacho, 2018). In that study a few conclusions are:

- It seems to work primarily to introduce non-design experts to a new way of thinking, but the simplification can harm ability to address really systemic and complex issues.
- Academic literature does not tend to consider “systems thinking” as an explicit part of design thinking but rather a complementary part or specific tool, e.g., (Brown, 2009).
- Comprehensiveness is required and implied, both in time and space. However, such an anticipatory design strategy is implicit at best in terms of how wide the system under consideration is stretched. Likewise, there is no clarity on the width of cause-effect and other interrelationships that should be considered in particular for the longer term.
- Similarly, the importance of disciplinary diversity and empathising with “all stakeholders” as prerequisite for successful design thinking is stressed by its protagonists, but it is not evident how broad that diversity should be and along which dimensions, besides functional disciplines. This suggests a clear area for more research.
- Human and environmental well-being are not explicitly seen as primary goals of design thinking, even though human-centredness as principle might be interpreted to imply that.
- Thinking in terms of small gradual improvements is thought to lead to global optimisation in time and allows for adjustments along the way. This is positive because there may be no known solutions yet to a challenge. The almost unavoidable consequence is however that such step by step optimisations create path-dependencies that may not be conducive to lead towards a best overall result is another matter.
- Currently both practice and research on integrating foresight into design thinking are scarce. In other words, there is room to explore the time-aspect and how it should be taken into account in the design thinking process.
- Working with low-resolution prototypes implies taking risks but can help to reframe the problem if necessary.
- Analytical mastery and intuitive originality need to work together, i.e., typical business and design skills need to be combined (Dunne and Martin, 2006).

As final conclusion of this meta-analysis five characteristics were proposed, shown below, as a forward-looking integrative overview of design thinking. While these five proposed characteristics together are not by definition a benchmark, it may be an interesting list to discuss later on, how the results of the empirical part of this thesis compare to this list, e.g., in terms of added value, usefulness, completeness.

- Comprehensiveness: widen vision of given context, consider unexpected relations.

- Simultaneity: develop understanding of the problem while developing the solution.
- Iteration: perform design cycle activities repeatedly.
- Graduality: gradual increase of understanding as input to gradually improve solution.
- Divergence/ convergence: alternate between diverging (creative, more intuitive) thinking and converging (more analytical, synthetic) thinking.

3.1.4.4 Systemic Design, Systems Oriented Design

Systemic Design and Systems-Oriented Design (SOD) find their roots in soft-systems methodology (Checkland, 1981). Systemic design principles have been formulated (Jones, 2014) as a concrete step to let a systems approach explicitly converge with design. The SOD development (Sevaldson, 2013, Sevaldson, 2017b) is related and on the one hand seems quite tool-based, on the other it stresses the typically designerly qualities to make sense of complex, multi-layered problem landscapes. Well known tools in that sense are Gigamapping (Sevaldson, 2011, Sevaldson, 2017a) and synthesis maps (Jones and Bowes, 2017) which together contribute to creating a rich design space (Sevaldson, 2008). The active use of visualisation tools according to some is one of the most important contributions that designers can provide so should always be at the forefront (Verganti, 2017). On the other hand, there is a risk that too much emphasis on skills like visualisation and drawing may be used as an excuse to move designers away from taking on a more strategic role (Bjögvinsson et al., 2012). Nevertheless, the emphasis on visual skills was re-stated in a recent dedicated special issue (Barth, 2018). Continuous development and increased use of visual and more general systemic design approaches gets primary attention at the annual conference Relating Systems Thinking and Design (RSD). This is possibly the most reputable venue for the part of the design-domain that combines systemic thinking and design skills. This is discussed further in section 3.5.3.

3.1.4.5 Fuzzy Front End

The design process notion labelled as Fuzzy Front End (FFE) is not explicitly systematic or systemic, but is aimed at opening up the search space, in all directions (Reinertsen and Smith, 1991). Perhaps ironically, an all-encompassing definition or dominant framework has not been developed yet (Hüsig and Kohn, 2003). All is possible, so little concrete guidance is provided. Emergence and redirection may occur but not in a planned way. This leaves open the possibilities that the unpredictability and uncertainty of a complex system can give back (also see section 3.5), but does not really give much direction how to proceed through the maze. The vagueness can be both a problem to create a shared vision (Zhang and Doll, 2001) as well as an opportunity to have an open dialogue without being inhibited. In practice the designer may already have a specific idea or product in mind and critically questioning the stated societal problem to translate it into a design challenge then is likely to be influenced by that initial idea. The FFE is considered to be roughly the period between the "first consideration of an opportunity and the moment when the ideas are judged to enter the structured development process" (Kim and Wilemon, 2002), and can take roughly 50% of the overall development time of new products (Smith and Reinertsen, 1998). Its place as well as resource-use provide arguments both for keeping an open mind, as well as getting to a point, not to be confused with the one and only point. Opinions vary whether the dominant mode of working should be that of interdependent activities (Kim and Wilemon, 2003) or a more structured sequential approach (Husig et al., 2005).

Further design relevant schools of thoughts are addressed in section 3.5, in particular with regards to how they respond to and address the increasing dynamics and complexity in society.

3.1.5 Fundamentals for systematic design engineering revisited

Having discussed the rich history of systematic design approaches, a few fundamentals of systematic design in general as identified (Beitz and Pahl, 1992) can now be more easily understood. In this section, these fundamentals that they identified - intuition and discursiveness, problem analysis, synthesis and division of labour, all printed in bold in the text below - are linked to the design characteristics (underlined) that were introduced in chapter 2. In that way we can explore how both important ways of reflecting on systematic design engineering relate, or not. This exploration feeds into a conceptualisation how systematic engineering might evolve need to further. That conceptualisation is outlined in section 3.1.6.

<u>Systematic variation</u> is currently hardly applied to investigating the problem-landscape (**problem analysis**) upfront, i.e. before the design task is set, and formulated in a design brief. We can clearly see this in the common narrow scope of a design task in the form of one particular context. Applying systematic variation to the period *before the design task is set* (e.g. avoid premature focus) would enable and encourage the inclusion of contributions from people with different specialisations and/or different contextual perspectives to contribute to addressing the different sub-problems. The result of such a design process, both in the **analysis** and **synthesis** phase is then likely to have a more integral fit with the larger system, and therefore a higher chance of addressing the problem on a larger more systemic scale. In that sense, the notion carefully emerges of a product-service architecture as result of a design engineering process as opposed to a product itself.

If the characteristic of systematic variation is indeed used *before* the definite design task is defined, the wider range of perspectives that is included encourages a more holistic and diverse view on <u>how to decompose</u> the problem. It is then therefore more likely that aspect-systems receive more attention, and therefore *relations between components of the system* are respected. With decomposition in sub-systems components are separated from each other without much attention for their interrelations ("aspects"). The latter is however more popular because it better matches the way how humans think: breaking something big up in components. Going for the less obvious option (hierarchical decomposition in aspect-systems) opens the (mental) door to work towards product architectures that allow a fit with more diverse requirements.

In this light, a more conceptual but all the more relevant decomposition example than the one of the car in chapter 2 would be the domain that was mentioned in section 2.1.1: a problem like clean cooking is experienced in multiple contexts and multiple use-cases within this range of contexts. The practical and appealing choice would be to divide the overall problem in sub-problems and system into sub-systems. The designer can then comfortably choose on one sub-system in the form of a particular context with the clear task to optimise the design outcome for that one sub-system (context). In this example of clean cooking a context in practice is often delineated by geographical boundaries, and choice for that context often gives strong direction for selecting one main user-group within these boundaries. The solution that is designed and optimised for that sub-system (context and user-group) is then inserted into the overall system, i.e. the global landscape of clean cooking contexts. As has been proven in practice, the problem for the other 'sub-systems' (contexts and user groups) where the problems regarding clean cooking are also experienced, is then seldom addressed because the relations with that part of the system have not been taken into account. The latter is exactly the gap that we identify for systematic variation. It is at this intersection with hierarchical decomposition into aspect-systems, that there seems to be the most promising improvement potential.

Even more, once systematic variation is applied before the design task, thereby gaining more relevant early insights about the problem as a whole, thereby increasing the odds for a more sensible hierarchical decomposition, the third characteristic satisficing has a different dynamic as well. Whenever a problem is decomposed, a **synthesis** of partial solutions has to take place later. Whereas in design tasks with limited scope the extent of satisficing may be limited because different requirements may to a larger extent point in the same direction, with a broader scope it is likely to be more extensive. In other words, design engineers are *forced* to get better at the art of satisficing while still achieving good results. This art or ability will become increasingly important, because due to increasing complexity reductionism-driven optimisation is not going to be an option any more.

As a general expectation, a design process where complexity, i.e. a diversity of interrelations that represent an inherent level of unpredictability, plays a larger acknowledged role is likely to be even more **discursive** in the sense of non-linear and with possibility to constantly change the sequence of activities than a normal design process. Contemporary design challenges are fairly complex, cause-effect relationships are non-linear, patterns in information may be more important than data points themselves and acting effectively requires moving from an unconscious process to a conscious one through rules, task formulation and procedures. If, as suggested above, the process and decisions are fed by a wider range of sources, this increases the odds that unexpected jumps and shifts take place. The choices to move between steps, and bring together potentially widely varying insights requires more of the **intuition** of the design engineers. In short: early stage systematic variation implies more discursiveness (i.e. non-sequential or even non-linear thinking), and it is not a strange thought that more of such thinking also demands a stronger use of **intuition** additional to pure analytical skills. Even though this last thought-step is slightly intuitive itself, if considered reasonable it would imply that this key skill that designers are alleged to own (Verganti, 2017) will be in higher demand.

With such fundamentals and characteristics taken together, it seems to be prudent to consider that the emphasis on product development managers or people with similar job titles as coordinators for such a process (Beitz and Pahl, 1992) might be ready for an update: the **division of labour** might be organised differently than for a single product.

Taking this sub-section together in textual form yields the following summary, which feeds into a more visually oriented conceptualisation in the next sub-section:

Considering formulation of the design task through a variety of possible contextual lenses before the problem has been defined (systematic variation before the design task is set) encourages a view that acknowledges relations between use situations and therefore definition and hierarchical decomposition of the problem into aspect-problems (and thereby aspect-systems) instead of sub-problems that occur in sub-systems. This type of decomposition, even if applied loosely results in a wider variety of requirements which therefore requires composed levels of satisficing. Because these considerations have kept interrelations between different aspects of the problem and system alive, partial 'solutions' have taken these interrelations into account, resulting in a more integral view on next (product) development steps, i.e., an inherently adaptive product architecture from which variations to serve different scenarios (implementations in different contexts) can be easily derived. This inherently more adaptive result is driven by an intrinsically discursive process which touches all stages in a design process without a given order. This requires an enhanced level of intuition on top of more analytical skills.

3.1.6 Towards a next step: visual conceptualisation

Summarising section 3.1 in a nutshell: while a clear focus per phase in a systematic approach as it has been done for over a century provides a useful basis, it may be questioned whether that basis is sufficient anymore to address increasingly complex contemporary design challenges. The elaborate contemplation on the history of systematic design engineering will result in suggested ingredients in 3.1.7, that will feed into the framing of propositions for the empirical part of this research.

First, as the summary at the end of section 3.1.5 announced it is possible to see the contours emerging of an approach that seems better suited to address the multiform complexity of many contemporary problems. Figure 3.1 therefore shows an alternative for the benchmark of a regular design process that was depicted earlier in figure 2.2, in exactly the same style. Because the differences with figure 2.2 with regards to the activities *within* the design task are not fundamentally different, the core of the design process on the right side is now depicted by one rectangular box comprising of all design activities. The left part of the visual is also the same as figure 2.2. These similarities emphasise where the focus of the reader should be: the start of the process (top of the visual), and the main effect on the outcome (bottom).

To enhance readability, in the remainder of this thesis the design engineering approach that complies with this visual and the brief explanation below is called Context Variation by Design, henceforth abbreviated as CVD. It revolves around the main principle of *systematic variation before the final design task has been set and clarified*. This variation generates the different contextual perspectives (X1 … Xn) on the problem, thereby allowing to formulate a multiform design task. In visual terms this variation is shown by the delta (Δ) sign now at the start (top of the figure) instead of just during the different steps within the design task (as shown by the three delta signs Δ on the right hand side). As can be seen, the main difference with the regular process is this *additional* use of systematic variation in the only place where it is not yet commonly used. This difference eventually results in a design outcome that represents a well-informed architecture that is can be used as *basis for implementation in multiple contexts* instead of a “solution” for one context; the specific sub-set for the **first context** where it will be implemented (X1) is an integral part of the architecture.

A textual representation of CVD 1.0 is provided in Appendix A2.1 in the form of a Abstract that represents how it has been communicated in the period when the birth of this thesis was considered, after the working paper was finalised (Kersten et al., 2015).

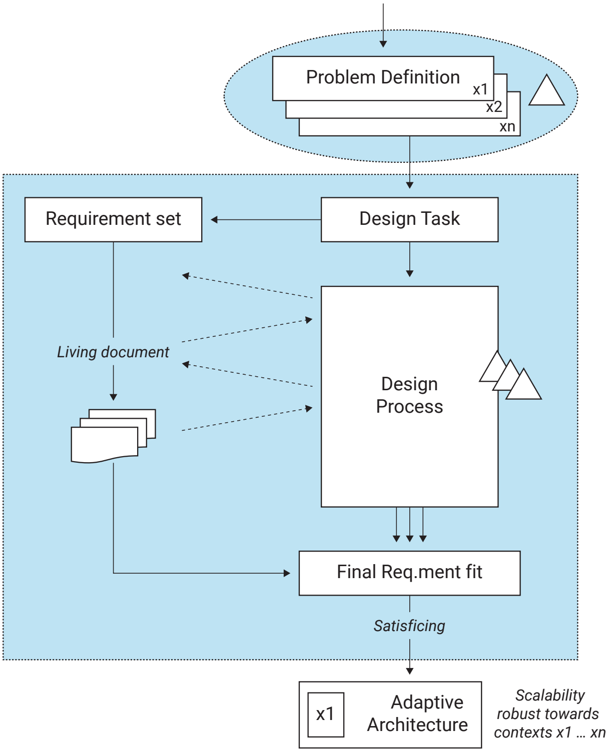


Figure 3.1 Enhanced systematic design engineering process – CVD 1.0

While the design process is largely executed along the same lines as in the regular process that was depicted in figure 2.2, the steps are driven by a multi-contextual energy. Because the design task reflects the multi-contextual nature of the problem, the odds are better that this architecture is not just adaptive to known differences, but also more inherently suitable to play into for less predictable requirements or so-called unknown unknowns (Snowden and Boone, 2007).

3.1.7 Ingredients for propositions

This extensive description of the evolution and general development of design engineering methods in this section 3.1 yields the following ingredients, including open questions, that can be taken into consideration when formulating propositions for the next-step exploratory research. Note that these ingredients, as in next sections, do not need to take the form of propositions yet.

- Systematic variation within an established design task has a rich and impressive history in design engineering but it focuses on the execution of the design task. Why not also apply it explicitly to the scoping of that design task? (see figure 3.1)
- Systemic thinking is explicit in many design engineering methods, but the width and diversity of the system that the designer takes into consideration is not always made explicit. If early systematic variation has not occurred, how broad is this system and is it sufficient?
- Focusing on one context and associated main user-group may give direction that is *too* rigid but without a systematic approach how wide and far should the search for further inspiration for design choices reach?
- To encourage decomposition of a problem that takes *interrelations between contexts* into account, a mindset of thinking in terms of aspect-systems is probably more conducive than one in terms of sub-systems
- If explicit insights are gained in real-life requirements from multiple contexts and user-groups, a possibility is created to develop a product architecture in an informed way, as opposed to a product that is optimised for the requirements from an initially narrow scope.

3.2 The contemporary business landscape

Design engineers operate in a context of organisations. While the use of design principles by now occurs in several environments, in this section the focus lies on the business sector. How does the business angle shape the manoeuvring space for these design engineers? This section is mostly descriptive, the next ones (3.3 and 3.4) subsequently emphasise the consequences and a deep-dive into the case of low-affluence target groups.

3.2.1 A brief history of growing global interdependencies

As hinted at in figure 2.3, the main driver that has shaped society, and business therein, in the years after WWII is globalisation. An essential point to understand about the effect of the globalisation of society is interdependencies. In this section the focus will lie on such connections rather than on end-points, e.g. best performing single entities. By zooming in on the interdependencies, the aim is to obtain insights for design engineers that will matter to them yet are currently not always their main focus.

3.2.1.1 The general concept

In the past millennia globe spanning connections did exist, most notably shaped and accelerated by traders and explorers (Frankopan, 2015). These connections were at first not very abundant yet and it was doable to have a functional overview of the relevant ones. It was also relatively clear how intertwined such connections were, or not. Thereby it was also reasonably predictable what would happen if you ‘push a button or pull a string’ at one side of the interrelation: if the originator of an action took that action, it was more or less clear what the result would be in most cases. Not anymore. This is one thing the financial crisis at the last turn of the decade has taught us: it started with obscure financial products in one country (Ferguson, 2008), but through unchecked and badly understood wide-scale entanglement of financial and other institutions, these interdependencies affected just about anything and anyone who was, sometimes without actively realising it, caught in that web. Closer to home for design engineers: an example of that complex entanglement could be the choice of materials to use in a product design, some of them scarcer than others, perhaps possessing superior properties, but creating dependencies that can have political ramifications. In the global society of today such ramifications may materialise so fast it is almost impossible to stay ahead of them (Frankopan, 2019).

As a consequence it seems unavoidable to explicitly consider connections and interdependencies or even, with a sense of intentional redundancy “mutual interdependencies” (Thompson, 1967). It might even be wise to do this also if one’s immediate scope does not seem to extend beyond nearby boundaries. Put differently: when in doubt, by now rather assume that the scope of the problem and how widely it occurs that you are considering is more interconnected with a wider system than you can directly observe. This seems to encourage to make use of notions that give new value to connections, like collaboration between teams in different contexts (Najafi-Tavani et al., 2014), forging new types of cooperation and involve new types of actors (Le Ber and Branzei, 2010) and considering different types of end-users (Stappers et al., 2009). This does raise the question *how far* to stretch the system under consideration so the multiformity is respected sufficiently. In reality practical circumstances play a large part in determining how broadly you can afford to look. The main point however is: you can, almost without exception if you are a contemporary company, not afford anymore to *not* look broader than your initial product idea suggests and the expansion may occur in any direction (Wooldridge, 2010). This is a similar observation as when inclusiveness was discussed in chapter 2. As is becoming more and more apparent, consciously considering the existence and relevance of interconnections means that conscious insights on the (possible) *effects* of these interconnections can more productively feed next steps (Morin, 2008). This by no coincidence aligns with the increasing popularity of systems thinking discussed in 3.1.4.

3.2.1.2 The main shifts since WWII

The general acceleration and diversification of globalisation is, though not the core of this thesis itself, certainly a relevant factor. Therefore this section now provides a quick-dive into this acceleration, focused on shifting innovation paradigms in the past century.

We can see that global business expansion up to a few decades ago was dominated by the internationalisation perspective of life cycles (Vernon, 1966). Developed countries in that perspective were both source of idea and production, then production moved to lower-cost countries or regions that could also serve as secondary market. Next, the somewhat more intricate relations between subsidiaries and innovation flows was acknowledged (Vernon, 1979) including possibilities of different origins for innovations based on certain specialisations (Cantwell, 1995). This was still a perspective that survived until this century (Petrick and Juntiwasarakij, 2011, Aulakh et al., 2000).

Only from the 21st century onwards did serious acceptance start of non-OECD countries being possible sources for innovation as well as execution, with the rise of terms like blowback innovation (Brown and Hagel III, 2005), reverse innovation (Immelt et al., 2009, Govindarajan and Trimble, 2012, Corsi, 2012), polycentric innovation (Radjou, 2009, Van Beers et al., 2013), jugaad innovation (Radjou et al., 2012), frugal innovation (Radjou and Prabhu, 2015), grassroots innovation (Gupta, 2003, Hossain, 2016), international innovation linkages between different types of companies (Benavente et al., 2012), bridgers within international companies (Washburn and Hunsaker, 2011) and many others (Agarwal et al., 2017).

With all these innovation concepts now becoming more known and practiced, in the second decade of this century it is more widely acknowledged in academics and practice what in fact has been reality for thousands of years: literally any place on Earth can in principle be both a source for innovation, as well as (initial) recipient and driver of the execution. However, as was already alluded to in figure 2.3, this is not the most important insight. For innovators, and thus designers, to keep being successful in the current age of the dominant importance of sustainability, it is much more important to capitalise in the best way on grasping interconnections and having some sense or at least respect for of the non-linear effects of the interplay in this web, or network, than on controlling the end-points, e.g., (Ferguson, 2017). It does not seem to be a coincidence that *patterns* are properties of the connections or the web, not of the individuals or the parts or the *end points*. This is also the core characteristic of complex systems (Stacey, 1996, Wheatley, 1998) and sustainability (Ceschin and Gaziulusoy, 2016). If we transpose this terminology on the product (development) domain we might consider the limitation or even impossibility of a single product covering a (global) diversity of requirements, i.e. the aforementioned “end points”. If the aim is to still effectively serve this global diversity, the way how to achieve this challenge, i.e. “the pattern”, points at the need of something other than a single product and points at the need for a pluralistic attitude that opens up instead of closes down (Stirling, 2008). This is discussed further in next sections like 3.5, in more explicit relation to design engineering as well.

On the other hand it should be realised that some of the paradigms that were mentioned, in particular frugal innovation and even more so grassroots innovations are not necessarily initiated with a large scale in mind at all (Bhaduri, 2016). They tend to be initiated by innovators in resource-constrained settings who experience a problem in real life and attempt to solve it with the limited means at their disposal. Their efforts are characterised by rootedness in a particular community, preferences of that community and an anti-centralisation approach (Hoppe et al., 2015). If the innovation works, others might well be interested, and might even be able to use it, and the innovation thus reaches a large audience (scale). Efforts to take these steps from successful usable invention to large-scale adopted innovation are however not the primary concern of the inventors. Their primary concern was to solve the problem that their own community was facing, little more. This might be why “*intentional* scalability” and “grassroots innovations” cannot easily be linked, through no fault of the initiator. These types of innovations, and especially the often creative thinking that has enabled their creation, can be a source of inspiration, but are with possible exceptions not the cases to look at in terms of scalability.

3.2.2 General business drivers in a nutshell

Notwithstanding the evolution in innovation dynamics, the dominant drivers in the globalised business landscape are still time-to-market and economies of scale. To manage these factors, there is a management prevalence for control and predictability or certainty as basis for major decisions (Mundy, 2010). In order to create a predictable financial course, such seeming certainty is for example being enforced with the use of so-called S.M.A.R.T. targets: Specific, Measurable, Attainable, Realistic and Timebound (Doran, 1981, Piskurich, 2015). Such highly measurable targets encourage to focus on highly measurable goals, like reducing costs through efficient production systems or increasing profit by increasing margins. Anything jeopardising this type of simple control is not immediately met with enthusiasm. Likewise for any method or strategy that reduces (perceived) manageability.

At the same time it is very clear that the operating environment *is* getting more **V**olatile, **U**ncertain, **C**omplex and **A**mbiguous by nature, or with an increasingly common acronym: VUCA (Suen, 2015, Bennett and Lemoine, 2014, Mack et al., 2015). We do see an emerging school of thought that warmly embraces not just the power but the necessity of dealing with situations that are labelled as VUCA. This amongst others requires sourcing in as diverse as possible perspectives (Tett, 2015), rather from the edge of your network and changing rather than from the core and stable (Stacey, 1996) in order to generate a rich overview that respects the multiform nature of most contemporary problems (Suen, 2015). Along the same lines it seems more advisable to use a range of models that all focus on different parts or angles with regards to the overall picture instead of relying on one dominant model. Further implications are included in next sections, but it seems safe to state that setting S.M.A.R.T targets, see previous paragraph, is not the best way to address VUCA challenges.

3.2.3 Global companies, local demands & low resource settings

As touched upon in chapter 2, in resource-rich (i.e. affluent) settings a strategy that allows either feature overkill or a universal base with a premium layer of – often digitally fuelled - personal customisation may work because people can afford the extra (unused) functionality or the premium for personalisation respectively. In short, in these situations there is – possibly unconsciously – less need for real thought through intent in design-choices to meet actual requirements.

It is therefore perhaps more relevant to focus on low-resource settings: feature overkill is not desirable nor are premium options. Therefore designing effectively, with meeting user requirements as well as scale-considerations in mind takes more effort. In practice this has often resulted in stripped versions of existing products (Qiu and Fan, 2013). The selected features then often do not match what users in different situations actually require. The result is a production system that is optimised for alleged efficiency, that does however not meet actual demands and therefore is far from effective. One might say that the focus is so much on the time-to-market that the longer term perspective, achieving impact on substantial scale in different markets, is not on the radar.

Redesign to match new situations is expensive and hampers scaling as we have seen in many examples (Kaplinsky, 2011, Meagher and Lindell, 2013). Especially in the context of Quality-of-Life issues this is not just undesirable from a moral and societal viewpoint but in fact also from a business point of view. Reality is more persistent however. As one case in point, both (Ideler, 2006) and (Wong, 2007) noted in their subsequent work on cookstoves for the same large principal that there was a need for built-in adaptation to new requirements. This knowledge has not noticeably been translated into concrete action. Because of lack of scaling the viability is often too low to proceed and specific learned lessons may disappear from the collective mind. As was argued by amongst others (Deaton, 2013), the previous industrial revolutions contributed to a divergence, also for the worse, so it seems a timely warning to make sure that this is not repeated and exacerbated by the much more interconnected drivers of the fourth industrial revolution (Schwab and Davis, 2018).

As mentioned in chapter 2, one contemporary label for such considerations is inclusiveness. The SDGs explicitly and implicitly promote inclusiveness for the coming decade of development as highlighted in chapter 2. In the currently dominant engineering methods inclusiveness considerations are not well met. This statement does *not* refer to a general lack of attention for disenfranchised groups of people per se. Rather it can be observed that attention for such groups when working towards specific products and services is often so focused, that the larger systemic landscape is not taken into sufficient consideration, i.e. seeing a tree but not considering the forest. Or, as often happens, the global problem-landscape in its entirety is covered but by a large number of unconnected and often small-scale actors (Ubels and Jacobs, 2018). In all cases here intelligence in the sense of various forms of knowledge, not IQ, and the sources in different places in the world where this intelligence resides is not effectively brought together. Most of this stems from the belief that different people and groups have such different needs that solutions should take that into account and including non-contextual intelligence has a negative effect (Khanna, 2014). This seems to be valid in cases where non-contextual intelligence, i.e. knowledge, experience and insights, dominates the design process without including contextual intelligence or where no specific contextual intelligence is used and universal products are introduced. In the development sector there is however a nascent realisation that alternative approaches are necessary, ones that acknowledge the interrelations and consider a networked approach to address that (humanitarian) challenges that looks more at the concept of complex adaptive systems (see later), than highly centralised linear responses (Ramalingam, 2013). Local knowledge and experiments are necessary ingredients but might benefit from more collective learning.

The consequence that is currently dominant is the separate development of solutions. As explained before, the indirect result is that in practice no solution effectively caters for a diverse range of disenfranchised groups in terms of enabling a combination of low costs, low prices and high availability. Therefore no solution becomes viable enough to survive. In other words, current processes might be inclusive on micro-level (considering in depth the needs of a particular disenfranchised group) but not on macro-level (considering multiple of these groups in conjunction in the same design process). This is relevant to such an extent that these consequences are discussed further in the next sections in particular in 3.4.

3.2.4 Ingredients for Propositions

As a result of the inductive and reflective process that was explained at the start of this chapter, the following ingredients are formulated to condense and synthesise main points made in section 3.2:

- How can we integrate the phenomenon of interconnections and inherent unpredictability that these create when designing products being more important than end-points in design engineering approaches?
- To which extent can products the design of which is optimised and production of which occurs with one main context in mind sufficiently meet a diverse range of needs and derived requirements that are relevant for a diversity of people?
- In particular for *emerging markets* how might design be organised to move from a focus on short term efficiency to one of medium and long term effectiveness, i.e., addressing the actual issue on a decent scale, multiple markets, and therefore achieving more impact?
- Might designing more inclusively, i.e. for a wider range of (disenfranchised) groups of people in society, imply that the balance of designers and their principals must shift from deep-dive with one target group of beneficiaries to a broader initial perspective?
- How can the concept of design choices pertaining to a multitude of target groups be decoupled from the strategy to design and produce universal products?
- How might a shift to consider multiple target groups be facilitated by a shift in management metrics that is conducive to catering for multiple target groups in terms of how accountability of managers in organisations is monitored?

3.3 Globalisation is real, dear professional mind the consequences

Since globalisation has accelerated the past 50 years or so, the consequences of the era of globalisation have also reached a level that needs to be acknowledged. This section addresses a number of consequences of the reality of accelerated globalisation. It will focus on three relevant categories of consequences when dealing with large-scale issues: products (including services), organisation (manageability under uncertainty), and finance (viability and towards zero marginal cost while scaling).

3.3.1 Product consequences: the end of design as we know it?

Many products that are offered in the global market place may not be 100% universal, but variations are often more cosmetic (colour, size, luxury features) than fundamental. Smartphones are a case in point. There are small variations in appearance and customisability thereof, but features are mostly universal and often overabundantly present, e.g., pre-installed but never-used apps. A socially more detrimental example is the domain of cook stoves, which is both one of the drivers of this line of research, as was demonstrated in chapter 2, and therefore a suitable theme for one or more of the cases in chapter 4.

Platform-based products can offer more flexibility (Martin and Ishii, 2002), but which width of specific, user-articulated requirements is explicitly taken into account? If this width seems substantial, might platforms that are put up without real vision not also encourage an attitude of design without intent? Referring to the pre-installed apps on a smartphone, on the one hand it can be argued that the totality of supplied apps covers a wide range of possible needs, for a user it is easy to add any number of them and in some cases obsolete ones can be removed. There is however likely to be severe influence on aspects like storage space, memory use, hidden energy consumption because there was not a holistic view on how users incrementally enhance their use. Just providing many options for which there is no obvious demand because the costs are close-to-zero is a form of feature overkill and – although formulated somewhat harshly - design-complacency. It may be conveyed as flexible but does not demonstrate much intent or effort in understanding what users need and want.

A strategy that seems to seek the middle ground is open-ended design (Ostuzzi et al., 2017), which openly declares some elements unfinished. The big question remains how informed these decisions are and what overarching intent for the product architecture lies at the basis of the decisions.

More general trends of mass personal customisation, 3D printing, build-your-own-X create an overall feeling of everything being possible, and this is usually presented as something positive regarding costs (Pearce, 2013), opportunities for new entrants (De Jong and de Bruijn, 2013), business model innovation (Rayna and Striukova, 2016) and more. But again: if everything is allegedly easily possible and end-users get more and more say in that after they have acquired (access to) a product, what is then still the purpose of design (engineering)? How does this development influence design with real intent and attention for articulated needs? If 'anyone' can design and become a producer, then why think about choices at all? To put a central point in this section in a blunt form: if everyone can become a designer of sorts, where does that leave the word that design is synonymous with, intent?

3.3.2 Managerial consequences

In previous sections many issues were listed that managers face when dealing with contemporary large-scale interconnected business challenges. In this section these explorations are taken one step further, in particular facing forward: what alternatives are suggested in literature?

First, to recap: there are several management consequences when dealing with complex large-scale issues, many of them quite obvious: management faces increased unpredictability and ambiguity, which cause a lack of oversight. While the necessity of multiple rather than singular perspectives is not denied, acting on it in practice turns out to be a challenge. And to top it off, the accountability system further exacerbates all these aspects of reality, so this unavoidable reality is now turning into a problem. Concrete examples of responses that represent these observations are control-orientation (Mundy, 2010), achieving quick initial success to secure funding buy-in (Ries, 2011), making targets S.M.A.R.T. (Doran, 1981, Piskurich, 2015), focus on control, objectivity and individual agency (Griffin et al., 1998), and setting clear boundaries between innovation stages, e.g. with stage-gates (Cooper, 2008, Cooper, 2014). None of these help managers in dealing with the VUCA-nature of contemporary issues. These are all in their own way remnants of a time when situations where -perceived to be - easier to gauge and agreement and control made sense (Griffin et al., 1998).

Fortunately, more thinking has been done on this matter. In particular, some experience was gained and research performed on how to deal with unpredictability and manage uncertainty, as far as it can be 'managed' at all. Much of it starts with a mindset that is conducive to not see unpredictability as a major problem. If it is accepted as a fact of life (Allen, 1998) that you need to work *with* instead of against, one enters a different energy-stream. This is exactly what is intended with the phrase "fight complexity with complexity" (Stacey, 1996, Nijs, 2014).

One relatively well known option to take into account a level of unpredictability is to work with scenarios (Levy, 1994). In that way it is possible to allow for distinguishing (sets of) circumstances and assumptions pertaining to these and devise a strategy-option based on these starting points. If the range of scenarios is wide enough, one might be able to play into different versions of reality once it is clear which version unfolds. It is not immediately clear how transitions or jumps between scenarios might take place, once it is clear that reality does not follow one of them. The quality of the scenarios in terms of actually increasing the ability to play into different circumstances, depends on the diversity of the people and models providing the input (Stacey, 1996, Jones, 2014, Tetlock and Gardner, 2016) but the mere concept of scenario-analyses already creates a different vibe than being asked to give the one correct answer.

Some interesting notions are for example offered by (Eisenhardt and Piezunka, 2011), with as general starting point the statement that organisations should be seen as a CAS (Complex Adaptive System). This implies that explicit attention needs to be paid to including a functional degree of redundancy in tasks and knowledge, ensuring sufficient diversity in backgrounds, and work with simple base rules to allow room for local autonomy to take decisions. All of this opposes the focus on more traditional drivers like efficiency, cost minimisation and (centralised) control. If an organisation indeed looks like a CAS, such drivers do the opposite of increasing adaptive capacity (Stacey, 1996, Allen, 1998).. Especially if tasks cannot easily be distinguished, simply throwing technology at it to combine data is not sufficient anymore and a more human component of actual collaboration is required to make sense of the data and turn it into actual collective intelligence (Malone et al., 2010).

In the same line of thinking (Iñigo and Albareda, 2016) take this up a notch and suggest more advanced concepts like accepting non-linearity, embracing emergence and thereby less predictable results, and self-organisation to effectively act on emerging insights. All of this is likely to be encouraged by an attitude that sees the value in emergent searching (Dunne and Dougherty, 2012) as opposed to focused finding. Requirements to lead in such situations are likely more familiar for organisations that are continually changing (Plowman et al., 2007). In these organisations juggling resources, encouraging experiments and embracing uncertainty are common (Lichtenstein and Plowman, 2009). There is likely to be an increasing demand for people who can create new structures emerging from apparent chaos, as opposed to following known structures (Furr et al., 2018). Local properties only get real meaning through their relationship with global properties (Goldstein, 2000), which again points at the importance of connections.

3.3.3 Financial consequences

The financial sector already started its globalisation process long ago, Because of the large consequences of 'getting it wrong', as a general rule funders in the public sector are risk-averse. They want to understand what they are funding so being able to tick boxes for them seems to be more sensible than doing something that does not fit in existing boxes. Companies and other organisations and even researchers may get influenced by that also when deciding on what to spend their time and money on. Doing something that is too different and/or transcends traditional disciplines does not fit in the mode of working of (public) funding bodies. Doing something different in practice therefore is notoriously difficult to get past approval committees.

Similarly for funding by business investors for trajectories that breathe uncertainty about gains and losses that are looming. When choosing between funding next steps on a relatively certain path or funding the uncertain or even unpredictable path (even if it is more exciting and more promising), in the vast majority of cases the decision will be made in favour of the former. The more certain path may not be without risks, but at least these are known factors and the chance of their occurrence and effects can be determined, they are known unknowns (Snowden and Boone, 2007). For uncertain paths, the risk-factors might be known but how to calculate them less so. If *unpredictability* starts to become a factor, it is even 'worse'. These paths will reveal unknown unknowns: the risk-factors themselves are not even fully clear, nor how risks might be calculated, let alone how acceptable they might be. When making transitions, short term financial performance is bound to suffer. This is a risk that can to an extent be quantified and thereby already constitutes a major blockage for the transition to occur (MacIntosh and MacLean, 1999). But worse, these transitions will also create dynamics that are not even known yet and therefore offer an even more daunting prospect for financers. Funders that strongly cherish to know exactly what risks they are facing and can to a reasonable extent calculate these will never venture in areas of unpredictability. Interestingly, but outside the sphere of this thesis to discuss in depth, one might wonder whether the fact that (private) financers have financial resources also implies that they have the knowledge and insights that enable them to make big decisions? Having earned one's fortune in an area in a time-period is not necessarily a good recipe for being humble about one's ability to make good business assessments in other situations (Tetlock and Gardner, 2016, D'Souza and Renner, 2014).

There seems to be a strong link to the cross-disciplinary field that is now known as behavioural economics: in this case the link is the framing of gains and losses, in particular the phenomenon of loss aversion or broader speaking "prospect theory". As the pioneers in this field have found in more detail (Tversky and Kahneman, 1991), people in general suffer from a strong sense of loss aversion. They perceive loss as twice as bad as a gain, even if the statistical odds are exactly the same and the odds are clear. In short, people psychologically respond stronger to avoiding downsides than increasing the chance for upsides. How this theory holds if stakes are high financially speaking has not been extensively tested (Harinck et al., 2007). However, a new strategy in all likelihood carries higher risks (known unknowns, certain uncertainties) but also more uncertainty (unknown unknowns). Taking this into account, foreseeable gains of a strategy change would probably have to be much higher than continuing with a current strategy, for funders to support that change.

Another driver for getting stuck in the so called stagnation chasm (Deiglmeier and Greco, 2018) is the underestimation of the different dynamics between the step towards 'proving' a solution on a small scale, versus scaling it to substantial level. This may be even more valid for development topics. In particular if more uncertain routes are chosen, then too few resources may be allocated or too many limitations put in place for its potential to materialise. Allocating more funding, while many uncertainties still remain, increases the financial risk and most funders do not consider this prudent.

One other interesting financial concept that seems relevant when dealing with large-scale problems and deciding how much diversity to allow in the product offering is the point of marginal costs. When assessing the (commercial) viability of an innovation at scale, it matters to have an idea about the *marginal* production costs, i.e., the *additional* costs, beyond fixed costs, that a producer incurs for *each additional product* (O'Sullivan and Sheffrin, 2003), i.e. the derivative of the cost function (Simon and Blume, 1994). If the marginal costs are not dropping with scale, it will be difficult to use scale as lever to argue an improvement of economic viability. As frame of reference, the *marginal* costs of many digital products are zero or very close to it, and could even become negative. A notable example being computer memory, but in theory also a product like e-books with the only likely costs being a license fee. Some argue that with more and more digital products that have this characteristic, and potentially energy supply moving in that direction, we may move to a zero marginal cost society (Rifkin, 2014).

In the context of this thesis, the core question that emerges is then, how can a physical product portfolio both meet a diverse range of requirements as well as show a marginal cost curve that trends to zero or even becomes negative? When considered in this light it is clear that in the scenario where for each new use case the product has to be redesigned, the marginal costs will certainly not have the desired strong downward trend. If one product is force fit into new use cases, the marginal costs may be low, but the product is also likely to not be adopted so the volume will be low as well. So, how can the two be combined: large-scale adoption *and* marginal costs trending to zero?

3.3.4 Ingredients for propositions

The following points are inductively constructed ingredients for the topics addressed in section 3.3:

- Many contemporary trends like 3D printing and DIY customisation can hollow out the role of design if the latter is interpreted as an intentional activity. Is that development unavoidable or can intent be kept alive?
- If managers, including ones that influence design engineering departments need to work with more volatile circumstances (VUCA), relying on traditional metrics and risk-calculation that guide their decision making is not sufficient anymore and the nature of metrics and what they can (not) measure needs to be rethought.
- Funding structures, in any part of the economy, need to be more geared towards accepting novelty if the intention is to facilitate instead of hinder inherently uncertain large scale innovation.

Measurable risks may have to be complemented with less easily measurable considerations, or ones with a sense of unpredictability built in.

- A design engineering strategy that contributes to or increases the likelihood of marginal costs trending to zero is one that will be welcomed by (financial) managers.

3.4 A level deeper: Issues vs Manifestations in low affluence settings

The richness of the exploration of combining an ever increasing globalised society and how it affects business and design, merits that we go a little deeper still. This is, as stated earlier true in general, but probably even more so in the context of large-scale societal issues in low affluence settings.

3.4.1 Same species, united by diversity

As argued earlier, the diversity in manifestations when turning to target groups beyond the initial one in practice often goes hand in hand with full or at least substantial redesign of the product (probably also the business model). Because by that time it has been heavily invested in, a main alternative strategy is to force fit it with no or only small modifications into user segments that have (partly) different needs. The common occurrence of these two situations was the status that was dominant at the start of the conception of this research. It may be expected that one or more cases that are selected in chapter 4 will demonstrate how too rigid thinking in terms of SMART objectives may not (always) be Wise.

An important role for the dynamics in the process to determine the width of the scope in the first place is played by the problem definition. This is possibly also one of the reasons why "globalisation" has come to be seen in a negative light by large groups of people: the interests of stakeholders active in shaping this global economy were seemingly not geared towards creating an equitable outcome (Stiglitz, 2008). Using one problem definition, whether focused on one's own context or one specific other context, for a globally relevant issue might seem to provide clear guidance for all stakeholders, but it also encourages them to steering towards universal solutions, often suffering from a technological path-dependency (Berkhout, 2002) and this is exactly the problem. What can be observed is that while on a higher level a problem can be formulated in a way that it seems similar for all concerned, on the level where it is actually experienced the similarities diminish. Once a problem has however been formulated in a certain way it creates the path for further steps (Myerson, 2015), including the search for 'solutions'. This does not encourage designers to do what they are supposed to be good at, i.e., look outside the system (Myerson, 2015), or look beyond the boundaries of academic disciplines when it is called for (Deaton, 2013), in part to increase the chance to assess whether their imagined 'solution' or metamorphosis (Sennett, 2008) might create unforeseen effects..

There seems to be an emerging case to actively avoid product development processes where activities in later stages demonstrate a strong path-dependency with the outcomes of a narrowly focused initial stage. This can be achieved by intentionally acknowledging real-life diversity. This is far from a new notion. In the updated edition of the seminal book Design for the Real World (Papanek and Fuller, 1972) it was already stated that products cannot simply be carried between contexts and cultures (Papanek and Lazarus, 2005). Nor is the notion specific to design. Developments like multi-sited ethnography (Marcus, 2009, Falzon, 2016, Hine, 2007) or more mainstream versions like out-of-silo thinking (Tett, 2015), intentionally seeking out farther-than-usual perspectives (Tetlock and Gardner, 2016) and embracing the experience of not-knowing as a positive incentive to investigate more (D'Souza and Renner, 2014) demonstrate that consciously thinking in a multi-context fashion has a broad, yet still small base of supporters. A poignant set of questions that then easily arises how diverse the perspectives should be, where they should come from, where in the process they should be sought out and how to add some structure or intent to this sourcing process. In practice, resources are finite. For designers, it was found that stressing the possibility to gain inspiration from anywhere, far removed from the problem-area, does not give the type of guidance that leads to useful results, while only allowing inspiration from to close-by can result in too little novelty (Gonçalves, 2016). Finite use of resources as well as finding the right level of 'inspiration' to work with are thus both relevant parts of the design reality to consider. To use finite resources wisely while still allowing for non-obvious connections, one might consider to think in terms of a range of design task-relevant areas to draw information and inspiration from. The range should be varied enough to allow creative connections, but not so wide that it would be purely a coincidence if these connections turn out to be relevant.

The finite-ness of resources, including time, may indeed be one of the reasons why the dominant way of working is one where not looking too explicitly at a diversity of contextual manifestations can seem to make much sense. It increases quick overview and control (Mundy, 2010), and may even provide a feeling of shared responsibilities and opportunities. But in practice it can and does easily lead to (over)simplification by pretending that the differences do not exist or do not matter or are not practical to consider yet and might lead to infinite variations to consider because of the broadness of the potential scope of the problem at hand. From a practical point of view simplification to avoid such variation is very tempting, and in fact encouraged by – in part previously discussed - calls for 'proof of concepts', lean development', S.M.A.R.T. targets, early success, or even early failure.

Even in processes that are governed by such characteristics, it is conceivable that a diversity of stakeholders has been involved (Van Tulder and Van Der Zwart, 2005); more often than not however these will still represent the ecosystem for a particular context (Taysom and Crilly, 2017). If a relatively simple solution can be developed for which basic demand has been established it can be quickly brought to production stage, with an efficiency effect (achieving economies-of-scale) looming on the near-horizon, which can then further accelerate adoption.

One main aspect that however seems to be overlooked when using this strategy is the possibility that the scope for the proven concept was too small relative to the diversity that often comes with scale. Once a first decisive step has been taken, a logical next step might rather be to focus efforts on making the developed solution to fit new circumstances with small tweaks at most (Dahlman et al., 1987, Harrison et al., 2009). There might be cases where this strategy works, but there is increasing evidence that proof on a small scale, e.g. pilot, may not be the best proof for success on a large scale (Ubels and Jacobs, 2018). Yet in practice it may be too tempting not to try and capitalise on the early success, in particular because it is also a favourite way of working for many funding bodies as discussed before. The seeming certainty that such a success on pilot-scale seems to provide in practice is the most sought after prize in early stages of innovation and deployment, while less attention is paid to reflect on the question what is being scaled in the first place: principles or products (solutions), causes or effects (Ubels and Jabobs, 2016).

3.4.2 Ingredients for propositions

Ingredients stemming from this section to feed into construction of propositions are listed below.

- Most contemporary problems that occur in society are not only multi-faceted but also relevant in multiple contexts in parallel, with similar and dissimilar requirements for pathways forward. How can this reality be captured, for example in the design task?
- How might the variety of requirements that comes with the different manifestations of the same issue, be respected while not drowning in an ocean of infinite possibilities?
- How can the scenario of path-dependent and heads down design (Myerson) be avoided?

3.5 Complexity: what is it and how can we use it?

So far in this chapter the focus was very much on the history of systematic design, and the more general history of an evolving (business) landscape. In this part they more or less come together. The growing interconnectedness in society combined with the evolution of systematic design rings one bell: complexity. This section therefore attempts to tie the previous ones together, and in that effort creates some functional and intentional redundancy. What does complexity mean, how do different fields deal with it and what can the design engineering domain learn from other fields?

3.5.1 Characteristics of complexity in real-life

Formulated in its most simple, but essential, form a system that contains three or more separate elements is complex, i.e. inherently unpredictable (Kramer and de Smit, 1979). What makes something complex is the interconnections and dependencies between these elements, with intentional tautology called “mutual interdependencies” (Thompson, 1967). Anywhere up from three elements yields a system where small input variations in any one of the elements will lead to new, and unexpected outputs or behaviour (Monat and Gannon, 2015).

Some interconnections are clear, as are the results of a change in one of the ends of the connection, for example raising income tax by 0,1% has an unambiguous positive result on government revenues, a minute effect on purchasing power and little directly foreseeable other effects. In other cases this is much less clear, for example the effect of a murky Brexit-deal on historically sensitive border-areas worldwide, or closer to the design-home, the introduction of for example an AI-powered, sensing machine for human emotions in a super-market to guide their purchasing decisions. Some of the effects and interconnections are foreseeable or visible, some can only be felt or assumed. All-in all, because all these phenomena happen at the same time, the behaviour of a system as a whole is unpredictable. This nowadays is increasingly true for any “system”. However, it is not as evident what should be the scope of a system under consideration, e.g. for a particular design task, to keep this unpredictability to a manageable level, or alternatively, rethinking the need for manageability.

The more this realisation of complexity is allowed in the system under consideration, the less certain it becomes. This is a strong source of discomfort for many people (MacIntosh and MacLean, 1999). However, it is, as also is increasingly recognised, simply reality (Peat, 2002), or a “state of the world” (Norman, 2010).

Still, as has been explained by others (van Engelen and van Bommel, 2020) one can reasonably assume a certain behaviour if you know the starting and or environmental conditions (e.g., when riding a bike). One may not even fully understand a complex system (bike, plane) but with a combination of logical thinking, experience and openness to learn it is still possible to operate it by not falling rather than trying to ride or fly it in case of a bike or plane respectively. This is valid for “known unknowns”. As alluded to earlier we also have unknown unknowns (Snowden and Boone, 2007).

In general, as long as you have developed a capability to adapt, keep observing and interpreting and being ready to change your working assumptions before responding to a situation (Allen, 1998) it should be possible to deal with uncertainty, unpredictability and other consequences of complexity. These capabilities are however not fully common yet.

3.5.2 Main lessons from elsewhere

As stated above, one key to enabling oneself to not drown when faced with complexity is to not try to control and also not necessarily trying to fully understand the system. That is one step on the way to working with it (van Engelen and van Bommel, 2020). This does require on the one hand an attitude of curious inquiry, but rooted in a humility of not being all-knowing (Montuori, 2012) or even being explicitly not-knowing (D'Souza and Renner, 2014). Appreciating the beauty of that state may in fact be conducive to staying open to enter in generative collaborative dialogue (Montuori, 2011) which can benefit even more from cultural diversity (Sardar, 2010) and different perspectives (Linstone, 1989). Such diversity and looking beyond the edges of one's network (Pascale, 1999, Sunstein and Hastie, 2015) is likely to be one way to stimulate to feed off interconnections (Morin, 2008), instead of receiving a mental push back from them.

Certainty is very comfortable but unrealistic (Peat, 2002) and as stated before increasingly an illusion anyway (Flach, 2015). Instead of using uncertainty as impeding or even blocking factor in a process, something to be feared (Nelson, 2007), another strategy could be to make it less relevant or critical, for example by focusing on adaptiveness instead. This is exactly where the tension lies with too strong a focus, because that is what reduces the ability to take flexibility and adaptability into account (Levy, 1994). This is not a totally new insight. "A plan is useless, planning is indispensable" (Eisenhower). To be clear, this does not imply to take just arbitrary blind stabs because "Chance favours the prepared mind" (Pasteur). As these quotes from reputable persons show, there is a sweet spot where some degree of preparation and flexibility to change strengthen each other. "Look in multiple directions before you cross a street" (Kersten et al., 2019b).

Complexity implies a level of chaos, in the context of this thesis not to be interpreted in a mathematical way. But look through that chaos, or rather zoom out or change the angle to find new patterns, multiple times, and be prepared to find (surprising) new insights (Johnson, 2002). There might be debate whether design engineers really are by definition well-equipped to fight complexity as many claim (Buchanan, 1992, Cross, 2001, Nelson, 2007, Dunne and Martin, 2006, Norman, 2010). As is to be investigated further what for now can be stated more equivocally is that design engineers are well positioned to visualise this chaos (Verganti, 2017, Sevaldson, 2017b) compared to for example the average business-educated professional who might rather focus on the problem-solving aspects (Korn and Silverman, 2012). This potentially gives designers an edge in their options to effectively work with complexity.

As shown earlier, from the business domain it becomes evident that to even hope to work with instead of against complexity, in particular people in management positions need to let go of their desire for full control. This may be the hardest nut to crack, because tendency to control and create easy overview, e.g. by simplification (Backx et al., 2017, Chen and Crilly, 2016, Mundy, 2010), analytical decomposition (Diethelm et al., 2016) and reductionism (Nelson, 2007) is still a dominant factor. The alternative, to allow emergence of insights to materialise and instead of controlling these insights (Dunne and Dougherty, 2012) create the conditions for them to materialise still mostly collides with long-held views.

For design engineers to get some room for more unpredictability in their design processes, their environment needs to allow this. This requires a level of alignment between the level of 'working with emergence' that modern design-educated professionals might enjoy (Verganti, 2017) compared with the rest of the organisation. Let's zoom in a little more on the possible implications of the phenomenon of complexity for design engineering.

3.5.3 Implications for design engineering

As explained previously, this section both adds to the insights so far and unavoidably but advertently will have some redundancy as well. This represents the aforementioned web of interconnections.

3.5.3.1 Design engineering methods

Around the same time that the thinking that evolved into this thesis materialised, others were making similar observations. One of the developments in that regard was the introduction of Frame Innovation (Dorst, 2015), built on a longer tradition of reframing (Paton and Dorst, 2011). Reframing itself is not focused on finding solutions per se but on "changing the frame/ lens" through which a designer considers a problem. The extent to which the problem is being reframed, in more or less radical ways, very much depends on the viewpoints that are being used. That is to say, if designers very creatively and divergently come up with framing alternatives they might arrive at radically different problem formulations and derived from that different design tasks. The importance of divergence has only been actively realised from mid-20th century onwards (Cropley and Cropley, 2005). When reframing, one aim seems to be to focus on what *might become* possible, although this often goes together with a form of simplification as well (Paton and Dorst, 2011). There is however no real way to know how broadly designers look to arrive at this new framing because they always have their own perspective as an unconscious anchor. A designer might even try to pull together an interdisciplinary, transdisciplinary or multi-disciplinary team (Mulder et al., 2012, Montuori, 2013, O'Rafferty et al., 2014). In practice this always has limits which are most likely influenced by the contextual environment that the team and thus the designer works (Suen, 2015).

Frame innovation builds on the general principle by playing with the different elements of the Why + How = What equation, which does force designers to consider nothing as a given per se in the situation they are confronted with. This includes turning all dimensions into variables, which encourages an attitude of not making any assumptions. In terms of the consideration of contexts or use-cases, that could mean that any possible situation could be considered, but it is not evident to what considerations for the *diversity* within the scope of the design task it leads.

One way to organise early design stages differently is to indeed accept that an increase in resources may be called for, when dealing with large-scale issues. As argued before, it is likely to meet resistance from for-profit funders because, especially in emerging market context resources are not easily found. There do seem to be interesting developments, like the previously mentioned multi-sited ethnography (Marcus, 2009, Falzon, 2016, Hine, 2007). If a field that has always been known for its almost religious devotion to deep-dives in a particular context is opening up to the relevance of considering diversity in a more connected way than before, what might lessons for other fields be? And how to choose such multiple sites? What links them, what separates them, who could even determine what is relevant in that respect?

3.5.3.2 Design skills

Promisingly, the visualisation skills that designers in principle possess can be actively used to their advantage (Verganti, 2017) and result in holistic views (Blizzard and Klotz, 2012) on the situation or problem (Jones, 2015). By now several interesting tools are in use that act on this promise, like the aforementioned Gigamapping (Sevaldson, 2011, Sevaldson, 2017a) and synthesis maps (Jones and Bowes, 2017). People who use these tools are intentionally encouraged to identify and then use patterns that emerge from data and other information. One could speak of "higher level order emerging from lower level chaos" (Johnson, 2002). Such patterns might not easily be identified let alone comprehended by non-designers without such design-oriented tools.

These tools contribute to enabling designers to work with the implicit complexity on the one hand, and encourage a rich design space (Sevaldson, 2008) on the other. Most writing and practice with regards to richness of design spaces seems to refer to the use of different types of media; the inclusion or link with the field of sustainability is also made (Wahr and Underwood, 2010). The fact that designers are trained towards producing materialisations (Lindgaard and Wesselius, 2017) is another interesting notion when talking about richness and visualisation. More on this in the next sub-section.

One of the key skills for any design engineer nowadays is the ability to design in a human and user-centred way (Norman, 1988). However, seen through the lens of the preceding observations with regards to increasing complexity and interconnections, perhaps it needs to be considered from a broader perspective: which user (group) to focus on and why that group. Or why focus? Are they the only one suffering from the problem? What is the path dependency (Jones, 2015) that might be created by the heads down design (Myerson, 2015) that looms when applying narrow focus and do the benefits of that focus outweigh the drawbacks? To be sure, human and user centred design are assets in the arsenal of design engineers, but might need a revision to allow for the developments that were observed in terms of the large-scale nature of many problems that design engineers are asked to work on nowadays and inherent diversity that comes with that scale.

In terms of overall business and design strategy an emerging discussion can be seen on the theme how to work with the emergence of insights versus displaying a level of intent or as we might call it, "design'. On one end of this spectrum we see the muddling through-paradigm (Lindstrom, 1959) that as was discussed before some advocate to apply in design-oriented processes as well (Norman and Stappers, 2015). This way of acting revolves around "acting opportunistically" (Norman and Stappers, 2015) and letting insights coming from each step strongly influence the next one. While it acknowledges the uncertainty that is inherent to complexity, it may overcompensate for this uncertainty. Opportunistic step-by-step thinking has some pragmatic merit but does not necessarily encourage the desire to aim for achieving a grander idea and puts much value on *reacting* to the possible surprises that each small step might reveal, as food for determining a better direction. Showing purpose and determination (intent), while not sufficient in and of itself (Ma, 2019), can encourage a possibly more appropriate design strategy when facing complexity. Moving forward without encouraging a level of intent may be suitable for very long lasting processes with no vested outcome, compare it with in fact evolution (Dennett, 2017). For designers a lack of intent may not be an inspiring strategy to embrace. As a designer one may not have to fully shape the world, but being a reactive follower is also not what makes designers tick. It should be in their nature to think big and bold (Myerson, 2015), re-design themselves and experiment, including failing (Flach, 2015). This is also voiced by others (Schwab and Davis, 2018) who warn that we do not have to be satisfied with whatever life throws at us (default options) but we can indeed attempt to actively shape what happens.

One way how the value of these characteristics might materialise is by identifying "latent creativity" and unforeseeable generalisability (Cropley and Cropley, 2005) in the design results: by thinking more adaptively incorporate elements in the solution direction that allow to play into a wider range of circumstances, while not knowing exactly what those circumstances may be, as opposed to optimising for one known problem. Incidentally, the latter is what design students according to some studies tend to do, even when being encouraged by their educators not to (Oraklibel et al., 2018). Just shuffling forward one baby-step at a time seems to correspond more with optimisation than with creativity-driven divergence and synthesis.

3.5.3.3 Richness

The aforementioned notion of richness in design spaces seems to deserve a little more attention. Not much literature exists on what richness might *actually*, rather than intuitively, consist of in order for it to become a more defined construct as opposed to a mere notion. A known interpretation is the use of different media (Sevaldson, 2008) or richness of communication, with face-to-face interaction for example being richer than e-mail (Kratzer et al., 2010).

It is however possible to identify a few complementary, sometimes indirect, interpretations of the notion of conceptual richness in design spaces. Examples of richness in conceptual terms are statements that design results should represent multiple views (Oades-Sese and Esquivel, 2011), the dialogue should be generative (Sevaldson, 2009), the quality of the object is "above average" (Weick, 2007), "enlarges the understanding of the human condition" (Weick, 2007), is based on more detailed information available (Yin, 2017) or reflects that the whole is different than the sum of its parts (Koffka, 2013).

On the topic of something like a question or insight being generative, This is determined by the following characteristics according to (Bushe, 2013): it is surprising, it touches people on a deeper than mere cognitive level, it creates a relationship between the people in the dialogue and – possibly most importantly – it provides a new perspective. An interesting question then is how relevant that perspective is for the design task at hand. One might surmise that for richness to materialise in conceptual design spaces the volume of information needs to be larger rather than limited, but there are probably limits to the value of constantly adding more information, i.e. the marginal value of simply more information is likely to decrease and beyond a point just adding more arbitrary information does not add value anymore.

To which extent the existence of such notions and interpretations is known to design engineers and whether their use is more explicit or implicit is perhaps less relevant than the fact that several interpretations of richness that all emphasise different aspects exist in the first place. Against the backdrop of this section a question then emerges what the diversity of interpretations of richness might imply for its use in design engineering: is it useful for design engineers to think in terms of richness, what do they consider to be richness at all and how similar are their interpretations? For now these are open questions. At least now they are made explicit.

3.5.4 Ingredients for propositions

From the elaborate discussion on the nature and rise of complexity in general and its implications for the design engineering profession and design engineering methods in particular, following ingredients emerged to feed into the propositions:

- Embracing the inherent unpredictability that comes with complexity is an Art that also requires discipline. How can design engineers be (better) equipped to achieve this?
- Acknowledging and working with complexity can lead to “lower level chaos” but also to “higher level order”. How can design engineers make use of this?
- In the face of complexity the (conceptual) richness of design spaces seems especially paramount. Do we know and agree on what that means and is such agreement important? To what extent can a shared and multi-faceted understanding of richness add value to the work of design engineers and design literature?
- What elements of embracing complexity are both Scary and Necessary, respectively referring to facing increasing unpredictability and acknowledging that reality is full of unpredictability anyway?
- How can information be gathered in order to turn unknown unknowns at least into known unknowns, i.e. get a more explicit understanding of what you do not know (yet).
- How might a focus on creating value for people (Human Centred Design, HCD) be combined with the reality that not all humans have equal drives and necessities even when facing a similar problem?

3.6 Propositions and key defined constructs

Based on all preceding sections, in this final one first three key defined constructs are provided (3.6.1.) Secondly the various ingredients that – on purpose mostly in the form of open questions - were provided at the end of each section in this chapter are combined to form full propositions (3.6.2). These propositions are the main framework for structuring findings based on the empirical research. The results of the empirical research are intended to shed light on the level of plausibility of the propositions and thereby provide direction for the discussion on appropriate next steps for researchers and practitioners.

3.6.1 Key defined constructs

Amongst others this chapter was intended to discover whether key constructs could be found for the themes that are the subject of this thesis, i.e. systematic design engineering. The following ones are considered to be promising to be presented as defined constructs. Further examination in this thesis will amongst others result in a better understanding of these constructs and their interrelations and how that can help design engineers to address the main problem that was identified:

- **Contexts:** Large-scale problems in society occur in different environments and circumstances which means that such problems occur with a range of different manifestations. These different manifestations are one reason why it is important to distinguish these sets of circumstances, i.e. <u>contexts</u>. However, it is not automatically evident what distinguishes one context from another. A few obvious but generic ways to distinguish them are geographically (according to country or regional borders), geo-physically (terrain), climate-wise, economic (e.g., based on GDP, Gross Domestic Product, per capita) or based on broader development status (HDI, Human Development Index-score). Depending on the issue at hand, other types of distinctions might also be relevant. Acknowledging the law of diminishing returns, is not sensible to include every contextual variation in a design task. However, it is advisable to spend more time on investigating what the key dimensions are for the problem at hand that determine *design relevant contexts*. By investigating this early on, the actual design process will be wide (covering *several* contexts) as well as directed (*relevant* contextual choices have been made). This will save effort by not sourcing from arbitrary *design irrelevant contexts*.
- **Richness in the design space:** When applying this multi-contextual reality to setting the design task, the scope of that design task is made broader than currently is common, with intent. This broadness may seem daunting because it could lead to an increase in information that the designer has to deal with. It is therefore important to bear in mind that this information is not just abundant but the intentional diversity feeds the morphology stage (constructing solutions) with a rich volume of information, that is likely to capture the interconnections between the different contexts. To appreciate this, the <u>richness</u>-construct might need to be understood better.
- **Adaptive architecture:** If the multi-contextual reality is the new starting point then it makes sense that the design outcome is also relevant for that same reality. This means that a contextually optimised solution, even one satisficed for multiple requirements within that context, falls short. The desirable design outcome (product/ service and business model) would rather need to represent

the characteristic of satisficing between requirements from different contexts and have the form of an adaptive architecture that is robust towards different end-use scenarios (contexts). This implies that with at most small variations or releases the architecture can serve requirements in different contexts, that together represent a large scale. While an adaptive architecture, e.g., a highly flexible platform that together makes up a product family, can also be created by just using requirements from one context, there is no relevant information available in that case what elements should be flexible, modular, optional or fixed and any decisions on that are taken based on assumptions or guesswork. Keeping everything flexible would imply taking no decisions at all, i.e. basically leaving design (intent) out of the process. The actual product version that will serve the first context that is chosen for implementation is an integral part of the architecture.

3.6.2 Propositions

The ingredients that were suggested at the end of each section 3.1 to 3.5 are now used to inductively construct propositions. As shown in figure 2.4, this step was subjected to reflection and interaction with relevant stakeholders in the environment of the researcher.

These propositions are to be used as framework for structuring the reflection of the findings of the real-life cases in chapter 4 and the discussion on this reflection in chapter 5. The sequence of the propositions is not according to their priority but roughly follows the main angles: *design engineering arsenal* and *empirical framing*, with as clusters within the latter *angle sustainability/ scale/ inclusiveness*, *design engineering education and management considerations*. One might consider proposition 5 the linking pin between the design arsenal related propositions and the rest. Especially because of that reason it is suitable to be placed 'in the middle' of the list.

Note that a proposition does not necessarily refer to one specific section in chapter 3, but can represent a synthesis of notions from several sections. This is in fact suitable for the subject of complexity: patterns refer to relations.

Proposition 1: soliciting knowledge and insights from multiple contexts in the early stages of the design process gives rise to unanticipated insights. Such insights would have been unlikely, or even impossible, to have been conceived within the scope of one specific use case.

Proposition 2: by using systematic variation in possible contexts *before the design task is set*, a rich(er) conceptual design space is created that allows design choices to be well and likely even better informed.

Proposition 3: to adequately discuss the notion of richness in a conceptual design space, a shared understanding of this notion and its relevance for the design process can help to grasp the nature of the design challenge.

Proposition 4: by thinking in terms of a product/ service (/ business model) *architecture* as design outcome the inherent suitability of considering diverse use cases increases, even if they are not all going to be served from the start, or even in the future.

Proposition 5: design process outcomes, e.g. on prototype level, that are the result of systematic variation before the design task is set, have the potential to perform better, i.e. score higher on a wide range of performance-criteria.

Proposition 6: conceptual design spaces that are explicitly fed by insights from multiple use cases are more inclusive, i.e., attentive for the needs of more disenfranchised groups, than design spaces that focus on one particular target group.

Proposition 7: for design engineers and their managers to perform well for a complex design challenge, the business mindset has to allow a high level of unpredictability of the outcome of the design process because more factors are interacting than when a simple approach is used.

Proposition 8: junior design engineers / students who are willing to embrace complexity do not demand or require detailed process instructions.

Proposition 9: the willingness of design engineers and their managers and/ or clients to embrace external (i.e., real-life) complexity is affected by their level of fear of the outcomes necessarily becoming internally complex (i.e., high tech) products.

Proposition 10: to assist a mindset that allows more initial efforts (timelines, possibly costs) due to incorporating diversity of requirements, decision makers need to think in terms of time-to-markets plural instead of singular.

From here onwards and as already announced in section 3.1.6 and visualised in figure 3.1, the design engineering approach that represents the conceptualisation of the considerations in this chapter and the inductively constructed propositions is called Context Variation by Design, CVD in short. This name reflects the three main elements that emerge from the preceding chapters: 1. Using systematic *variation* to 2. Distinguish and subsequently involve different *contexts* 3. *Intentionally* and not in a piecemeal or ad hoc fashion. This approach takes centre-stage in the identification of relevant real-life situations and selection of cases to be described and reflected on in depth in chapters 4 and 5.

Chapter 4

Chapter 4 – Empirical cases - selection and results

After the extensive literature research, this chapter focuses on the empirical part of this thesis. The primary research approach is reflective and inductive which requires data-rich real-life cases as main material. The research is intended to be “emancipatory” and through reflection also aims to improve our shared understanding (da Costa Junior et al., 2019).

Section 4.1 starts with explaining how the empirical part of this research was approached, and how relevant real-life situations were identified and then reduced in number to arrive at a feasible list of cases that can be described and interpreted in full in this thesis. The list represents the selection of real-life situations that are *most eligible* to serve as illustrative cases. In particular this refers to their suitability to provide relevant insights for the areas that are touched upon in the propositions and the (access to) availability of high-quality information to construct these insights.

Each case ends with a list of findings with regards to how the empirical results of that case relate to the propositions. As also shown in figure 2.4 in section 2.3.2, the findings for each of the cases have come about by means of using direct sources (student reports, own observation, meetings with the designers, communication with designer and/or principal) and by using the peer-reviewed publication(s) that feature(s) the case. Section 4.3 inductively combines the case-specific findings into overarching, numbered insights per proposition. This step was executed by the researcher, while scrutinising the decisions with design experts in several rounds, thus turning the results from potentially subjective into intersubjective. These numbered insights function as a bridge to the next chapters. Finally section 4.4 is added to decrease the gap between the insights and the reflection on what that result means in chapters 5 and 6.

This chapter in particular contains references to different types of empirical information, or results from empirical investigation. To distinguish these various types related to empirical research, the different terms are listed below as *they have been used in this thesis*:

- Fact: element of information that is objectively considered to be true and by itself does not require deeper discussion.
- Observation: result of a personal sensory action (seeing, hearing, measuring).
- Finding: interpretation by the researcher of empirical results in the cases in light of the propositions, scrutinised through interaction with other research stakeholders, aiming to achieve further understanding of the subject-matter.

- Insight: deeper understanding on a topic, based on deep scrutiny and reflection on one or more facts and observations, revealing a not necessarily obvious inference from these facts, similar to "discontinuous discoveries, that is, non-obvious inferences from existing evidence" (Klein and Jarosz, 2011).

Note that the word "insight" is used to refer to the deeper level of understanding by designers in the cases, as well as the results of this chapter in section 4.3.

4.1 Real-life situations and cases: selection process

This section contains an elaboration on the nature of case-based empirical research and its application in this thesis in 4.1.1, the actual identification of a long list of relevant and available real-life situations in section 4.1.2. and selection of a feasible number of in depth cases out of this long list is presented in 4.1.3.

4.1.1 Step 1: Required characteristics of real-life situations and cases

As mentioned, the research in this thesis is inductive, meaning that eventual patterns are to be drawn from the cases. To make this work the information that cases provide needs to be rich in content. For a real-life situation to be considered as a candidate for providing this rich content, it in the first place has to comply with three basic criteria:

- Timing: it needs to be completed in time to be included in this thesis, i.e. by February 2019.
- Contents: in some shape or form, the CVD-approach (revolving around systematic variation before the design task is set) needs to have been used and consciously experienced by designers. As allowed alternative, the real-life situation involved explicitly discussing the absence of the use of the CVD-approach. This does exclude real-life situations from the past that were executed before the CVD-approach was suggested. While such situations might reflect thinking that is in line with CVD, a line must be drawn somewhere in terms of fixing at least one of the elements, in this case the design engineering approach.
- Information accessibility: information needs to be directly accessible to the researcher, and related to the scope of this thesis.

Based on the purpose to explore the possible added value of the CVD-approach in real life, and the need for sufficient access to information by the researcher, the search space for cases was for reasons explained in chapter 2 (section 2.3) – in practice – strongly related to the direct environment of the IDE-faculty. These situations are not purely academic ones because in most cases a real-life principal, often with design as one of their expertise-areas is involved, additional designers or similar at the case-companies act as supervisors, and design experts from the faculty assess design-specific aspects as well. In all situations design challenges are realistic and student-designers receive support from various professionals (principals, expert-designers, design-educators). Conversely, the explorative nature of the research does not match well with the conditions inside companies, with long throughput times, levels of confidentiality and – as proven by early conversations – reluctance to try out something that they would like to see explored in a safer environment first.

The real-life situations from which the cases are selected can be broad or deep (Yin, 2017). The former typically involve multiple designers working on a similar (small) assignment thus allowing some form of comparison. The latter typically refers to a full end-to-end design assignment, that usually takes a longer period like five to six months. Graduation assignments and final-group projects typically fall in this category.

4.1.2 Longlist of relevant real-life situations

When applying the main criteria and the main categories as described above, a longlist of 23 real-life situations was established for which information was available to the researcher. This longlist is included in Appendix A4.1. Of the situations in this longlist twenty were executed by MSc-level students from the IDE-faculty. One external situation was included where the researcher could converse with an external company subjected to an NDA (meaning direct access to high-quality information that can be used, but anonymised), and two graduation assignments by non-IDE students whom the researcher had personal contact with, who did actively use the CVD-approach and were immersed in real-life settings including active involvement by principals and/or other stakeholders.

4.1.3 Step 2: Reducing the longlist

While all real-life situations contributed to the collective experience of using CVD as design approach, not all of them were *equally relevant and suitable* to consider in-depth for the *purposes of this thesis*. Next steps were required in order to select the ones that most suitable and arrive at a feasible number to present in full detail in this thesis.

To go from the longlist of *available* real-life situations to a feasible list of cases to be included in detail in this thesis, the following criteria were used: These criteria are directly or indirectly derived from (Yin, 2017):

- Access by the researcher to high-quality data-rich information (detailed reports, face to face conversation, meetings as observer) that is suitable to generate empirical insights that are relevant for one and ideally more propositions. This is relevant as a filter because not all real-life situations, especially the early ones (chronologically), were set up and executed in a way that was immediately relevant for the propositions. In part that was due to the researcher not having control over creating this relevance in these instances.
- A physical prototype is not a mandatory design outcome required for inclusion as case as long as in depth analysis of the process and experience of the designers is possible based on the available information.
- In case the researcher is an active participant in the design process, measures have to be taken during the execution of the case to ensure objectivity or inter-subjectivity of data.
- Ideally the theme was a sustainability/quality-of-life issue because of the higher societal relevance for such issues than for mainstream products..
- Ideally, the real-life situation had been included in one or more peer-reviewed academic publications of which the PhD-researcher was (co)author. Thereby discussion of the cases had passed a form of academic debate. That academic debate can be considered as one more form of relevant interaction with the research environment (figure 2.4).
- On the level of the short list as a whole (portfolio of cases) there were additional criteria:
    - The portfolio of selected cases should contain both broad and deep ones.
    - The total number of cases needs to be feasible for the researcher to describe and interpret in relation to the propositions within time and other resource constraints.
    - The portfolio of selected cases needs to cover all propositions; it is nevertheless to be expected and acceptable that some propositions are covered better than others.
    - Any proposition should be reflected on in more than one selected case to reduce the risk of too much dependency on one case for that proposition.
    - The portfolio of selected cases should have the potential to yield results that can to some extent be generalised, or at least can be discussed with regards to that aspect.

Note that any expectation whether a real-life situation would support (or oppose) propositions was not a part of the selection criteria. The selection process was agnostic in that respect. The fact that the goal of the research is not to support (or reject for that matter) the propositions listed in 3.6.2 is one argument why selection of cases from the available real-life situations is not much in danger of being hampered by confirmation bias: support or rejection, or anywhere in between, of propositions are all acceptable results of this inductive research. To further safeguard any bias in the selection. as with the other parts of this research, the case selection was part of the process of continuous reflection and interaction with experts and others, as illustrated in figure 2.4. For the case selection this was done by means of, first, discussions on the arguments (criteria) that were used for the selection, the result of which is shown above. Secondly by means of discussions the extent to which the selected cases indeed complied with these criteria. Specifically, academic experts weighed in on the extent to which identified real-life situations from the longlist provided the best access to high-quality rich data and as a bonus were more eligible than other candidates (i.e. real-life situations on the longlist)because results had already received academic scrutiny because of their inclusion in a peer-reviewed academic publication. These steps were intended to ensure as much as possible that there were 'checks and balances' in the selection process.

For those interested in the analysis how real-life situations on the long list were related to one or more propositions and academically peer-reviewed papers as part of the case selection process, the results of this intermediate step can be found in Appendix A4.2.

When all criteria and considerations as described above were applied, seven real-life situations remained that are suitable to be included as detailed illustrative cases in this thesis. These are listed in table 4.1 below, including a new ID (first column) and relevance for one or more propositions.

#	ID from longlist (A4.1), short name	Year(s) of execution	Expected relevance for proposition #
1	#8, Maternal health care (Babyviewer)	2016	1, 2, 3, 4, 6, 7, 9, 10
2	#10, Gasifier cook stove	2016	2, 3, 4, 5, 8, 10
3	#14, Charcoal cook stove	2017	1, 2, 4, 5, 6, 7, 8
4	#15, Internationalisation course	2015 - 2017	2, 7, 8, 9
5	#23, Graduation experiences compared	2017 - 2019	1, 2, 3, 4, 5, 6, 8, 10
6	#16, S.PSS/SBM course	2018	7, 8, 9
7	#7, Alignment with management & funding	2016	5, 6, 7, 9, 10

Table 4.1 Short list: cases for detailed inclusion in this thesis

For completeness sake, below the check with the criteria on portfolio-level is shared:

- The selection represents a *combination of deep and broad cases.*
- Seven cases is *feasible*, in particular if some form of structuring can be used.
- The selection *covers all propositions.*
- *Each proposition is touched in more than one case.*
- The selection is diverse enough to at least allow *discussion on how generalisable the results are* and in what way(s).

In conclusion, this list of cases complies with the criteria as stipulated above.

4.2 Case descriptions, results and findings

Each selected case in table 4.1 serves as equally valid to be described in more detail in this section. For readability reasons and in particular not to disrupt the reading flow in the main body of the thesis too much, only two cases are presented here in the main text, the other ones are included in Appendix A4.3. Apart from their location in this manuscript, there is *no difference* in terms of how these cases are presented and used in the next steps. The cases that are included in this section are #3 and #5, numbers referring to the first column of table 4.1, as an example of a deep case and a broad case respectively.

For readability reasons it is desirable to present the cases using the same type of format, independent of how each individual case was executed. Like argued in the section above, their most important characteristic is that they provide *sufficient high-quality information in relation to the propositions, that is accessible to the researcher*. The format of all case descriptions is as follows:

A. Brief description of the actual case (type, theme, timelines, real-life stakeholders, localities, expected results, process, final result), and related publications.
B. Brief description of how the results are made relevant for the MRQ in this research and where relevant references to methodological or data-parts of related publications.
C. Findings by the researcher in relation to the propositions (3.6.2), based on a diversity of sources that represent the data-rich information from the case (reports, meetings, conversations, publications, of which highlights are included in parts A and B) and extensive interaction with stakeholders.

Reader navigation remark for cases: to avoid much repetition and self-referencing, in all case descriptions below and Appendix A4.3 when referring to own publications that featured the case the sequence numbers (Ref. #1, Ref. #2) refer to table A4.2 in Appendix A4.2. Only when there are as yet unpublished data and arguments based on these, the supporting data are specifically included here or in Appendices related to this chapter.

4.2.1 Case #3: Charcoal cook stove in Africa, deep

This sub-section covers case #3, as listed in table 4.1.

A. **Description of the case (contents)**

<u>Topic and timing:</u> This case study concerned an IDE Master graduation assignment on charcoal cook stove development that was conducted in 2017. The principal was a medium-sized charcoal cook stove producer located in Asia who was interested in exploring the African market and had actively contacted IDE to recruit a graduation student to work on this exploration.

<u>Goal of the project:</u> The cook stove design was intended to be in line with cooking habits in Uganda (East Africa) and Ghana (West Africa), which represented two distinct cooking ecosystem contexts. The expected result of the assignment within the scope of the student project was one testable prototype for both contexts.

<u>Process highlights:</u> The student used extensive reports and data, amongst others from previous student groups who had developed cook stoves in these countries, as well as immersing herself in the context on which the least information was available, making observations, conducting user-interviews and technical performance measurements as close to the cooking

process as possible. The project focused on People Technology Matching (PTM) in both contexts. Other considerations like supply chain, overall business model and marketing received less attention (Ref. #5). This focus was chosen because of the expected peculiarities of the different cooking contexts that need to be clarified first. Concept development occurred in the Netherlands after the field research, prototype development and testing was conducted at the headquarters of the principal, in Asia. Deciding on a timeline for follow-up actions back in the user-contexts based on the results was not within the scope of the assignment. The high-level process flow, and way how PTM and CVD were used together is shown in figure 4.1. The use of CVD is represented by the combination of different steps: the *parallel* research in and about two contexts, the shared design space where findings from both contexts were used with equal importance, the construction of an adaptive architecture and the easy distinction of the versions of the product for the different contexts based on this central architecture.

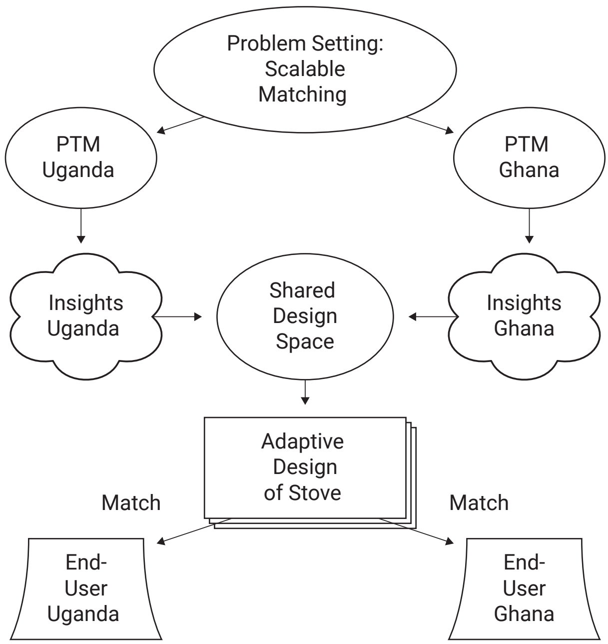


Figure 4.1 Combination of PTM and CVD in charcoal cook stove case (Ref. #5)

<u>Final result:</u> A charcoal cook stove architecture, integrating the technology of the principal with a range of cooking habits from both contexts, lab-tested for technical performance and ready to be user-tested once the principal would be interested in doing so.

Besides in the MSc-thesis itself (Van Sprang, 2017), the process, intermediate and final results and arguments for design choices were published in Ref. #5; all choices were extensively discussed in section 4 of that publication and some elements were also mentioned in Ref. #6 and Ref. #9. For ease of reading, some of the main design choices are listed here as well.

- Required for one context but still useful for the other, e.g., support both for flat-bottomed and as well as round-bottomed pans.
- Features that represent complementary requirements, e.g., power range from low to high instead of low-medium and medium-high. Each of the latter would have been optimal for one of the contexts, but would create problems in the other one.
- Choices that were essential to align with cooking habits for one of the contexts, e.g., location of air holes for draft versus habit of 'stuffing' pans into the charcoal.
- Optional features, e.g., gas hose extension to attach hose for LPG (Low Propane Gas), when this would be an affordable fuel (which in one of the countries was season-dependent).

B. Relevance for this thesis and research questions

The student was formally supervised by two design experts from the IDE-faculty. The role of the researcher in this process was to be an informal supervisor of the graduation student, as a sounding board complementing the formal supervisor (IDE-professor). No specific prescriptive advice was provided to the student in terms of *how* to execute the process or *what results* to achieve. The student had voluntarily opted to use the CVD-approach. The main goal in relation to this thesis was to observe a full design process where the CVD-approach was used, with enough time to take deliberate steps. The latter in response to feedback from students in preceding years, as discussed in Ref. #7, that a lack of time is likely to undermine any potential that the CVD-approach might have.

The student ensured that intermediate results of her research were verified by means of dialogue with the main user-groups from the different contexts (Uganda, East Africa and Ghana, West Africa) and by means of follow-up with other stakeholders, including the principal.

The main results, of which some highlights are listed at the end of Part A, have more extensively been captured in the peer-reviewed Ref. #5, in support of a presentation at an international conference. For more details: the major insights from each contextual research are included in section 3, design choices in section 4 and conclusions in section 5. Main shared insights for this case were also published in Ref. #6.

These experiences were subsequently input for presenting the process and design result at a summit for practitioners in Africa. Whereas the first presentation had generated modest positive response from the audience, the latter created a strong positive response. In particular in comparison with a preceding presentation on a -context-specific- cook stove, the 50-odd participants considered the multi-contextual mindset and approach, including its practical results, to be a welcome development for the cook stove domain. The reality of cook stove producers in Africa primarily developing cook stoves that were geared towards one context, even if they were well aware of differences in cooking habits, was explicitly confirmed. Consequently, the relevance of developing a cook stove (architecture) where contextual differences had been taken explicitly into account was acknowledged both as very relevant and not-common yet.

C. Findings related to the propositions

The main findings in terms of the propositions (3.6.2) are shown below.

For proposition 1: unanticipated insights are likely to be created in a shared design space

- After bringing all facts, observations and other empirical data together, several design choices were specifically based on combining requirements from the different contexts. It is clearly identifiable how relying on either one of the contexts for major design choices would have yielded different outcomes and would have resulted in choices that would have constituted a mis-match for the other contexts, e.g., for the power range, necessity of the pot-support, locations of the air holes and relevance of the gas hose extension, to mention a few.
- Because of the early insight in some conflicting requirements the design choices could make these conflicts largely irrelevant, possibly at the cost of optimisation for any of the contexts.

For proposition 2: a rich design space leads to well-informed choices

- Related to the aforementioned findings for proposition 1, the shared design space ensured that the designer by her own admission could make better informed choices for the design architecture than would have been the case if she would have worked with assumptions from either context, or without considering the other context. This point, the relation between the insights and subsequent choices was more extensively discussed in Ref. #9.
- As can be seen above (end of Part A of this case study description), some of the design choices concerned minor aspects, other were more fundamental.
- The relevance to combine requirements from different contexts early on was acknowledged by participants in a cook stove summit in Uganda; they stated that this has added value if scaling is within the ambition of the cook stove producer.

For proposition 4: considering multiple use cases contributes to an architecture mind-set

- In terms of the product design the resulting prototype contained elements based on the design choices that together do represent an architecture with options to leave out or include per context, and features that cover requirements from both contexts as opposed to one product with features optimised for one context.

For proposition 5: design outcomes following a CVD-approach potentially have a higher performance

- The technical test results for the prototype indicated a good performance in technical terms, relative to the information that was known from the use-cases. A next step would be to physically test it with end-users from both contexts for a real-life quality-assessment, ideally compared with a similar assessment for currently used stoves by these end-users.

For proposition 6: multi-contextual design spaces are likely to result in (more) inclusive results

- By explicitly taking requirements from multiple contexts into account the alignment with these different contexts is demonstrable. This automatically enhances the inclusiveness, at least on paper.

For proposition 7: to perform well in a complex design challenge, the (business) environment has to allow a high level of unpredictability of the outcome

- The principal was explicitly open to including multiple contexts in the assignment, even while their proprietary technology would have to be an essential component of the eventual design. Whether this would work out well was unpredictable, but this was not considered to be a blocking factor by the principal.
- The results of the assignment are intended to be the starting point for the principal for their move into the African market. Due to many circumstances, this is not expected to be done very soon. Whether it will happen is uncertain, and if it happens, the timing for now is unpredictable. Neither factor proved blocking for this project.
- The flipside of allowing unpredictability could conceivably be to consider an assignment as free-of-practical-obligation and therefore not important. More specifically, the delay of the *use of* the results of the graduation student by the principal might in theory have caused demotivation on her part. There is however no sign that this occurred.

For proposition 8: willingness by design engineers to embrace complexity implies not demanding or needing detailed instructions

- The lead designer expressed that using CVD primarily was valuable in terms of the overarching mindset during the assignment with regards to using a *contextual diversity of* sources and by no means resulted in excluding other design methods and tools. In that sense the relative lack of detailed instructions how exactly to apply CVD was not considered to be a problem.

4.2.2 Case #5: Graduation experiences, broad

The same format is used for describing the second main case study, #5 from table 4.3, even though the current one was more geared towards insights about the process than the detailed contents. Consequently part A is limited because the design contents of these cases are relatively irrelevant.

A. Description of the case (contents)

<u>Topic and timing:</u> In the period between the summer of 2017 and early 2019 the experiences of five IDE graduation students were evaluated in the same way. This was done by the researcher (see part B of this case description) on top of and independent from their formal grading process. All students had voluntarily chosen to use the CVD-approach. The five individually executed graduation projects were the following, including #ID from the Longlist (A4.1):

- 1: food habits in Asia and Europe (2017, #13)
- 2: health device for countries in Asia and Africa (2017, #12)
- 3: cook stove for different countries in Africa (2017, #14, the case study described in 4.2.1)
- 4: seaweed as prime component of bio-based materials (2018, #17)
- 5: high quality production waste as input for new products (2018-2019, #23)

<u>Expected result:</u> While all these assignments had a real-life principal in the form of existing companies with an actual design demand, for this specific case study the results of the design assignments as such are of limited relevance and are therefore not extensively addressed here. The evaluations were explicitly intended to yield insights on how the graduation students had *experienced* the use of the CVD approach in a relatively long and individual design process and its value, if any, in their total design engineering arsenal. This reflection did include considerations of the eventual results but these as such are not of prime relevance to this particular case as much as they would be in the deep cases.

<u>Process highlights:</u> The format of the evaluation form contained a closed and an open part. The contents of that form are described in part B below. For this part of the case description the only remark for now is that the students

all appreciated the opportunity to provide their reflection on the use of CVD, other methods and their entire experience, independent on how they valued all of these aspects.

Final result: The five students completed the form after their graduation defence throughout the period (2017 – 2019). The researcher had a meeting with each of them to ensure accurate understanding of their responses and the results were brought together for this case study.

B. Relevance for this thesis and research questions

By evaluating five graduation students in exactly the same way and asking them to reflect themselves, the intended result was the possibility of patterns to emerge from the totality of responses.

The role of the researcher was first to design the evaluation format. This was an improved version of an earlier version that was used in an MSc-course in which some minor ambiguities and unclarities were removed or modified. That initial version had been constructed based on dialogues with teaching staff and students on aspects, with negative or positive connotation, that are relevant when experiencing particular methods when using a complex design assignment. Examples of such aspects are *Encourages creativity* and *Requires mental effort*. Students were for that version asked to assess their experience of doing an assignment with and without CVD by comparing sixteen aspects (closed) and then reflect more extensively on the process as well as results. The details of the internal process to arrive at the initial version of the form are extensively discussed in Ref. #7, and case study #4 in this thesis, and it is not opportune to repeat it here. In fact one of the suggested improvements by several students in that case study was to use the form to evaluate longer assignments, which is exactly what resulted in this case.

The five graduation students who completed the evaluation form did so independently and the results were not intertwined with their official graduation-assessment in any way. The meeting that the researcher had with each student individually took place after their graduation defence to prevent any entanglement with their formal graduation assessment. After all evaluations were finished the results were then ready to be brought together and investigated to identify whether overarching patterns could be found in the responses.

The students for this case study #5 were asked to assess these aspects of using CVD *compared to all other methods that they had learned in their study*. The aggregate answers of the students are included below in table 4.2. The last column that is shown was not part of the evaluation form but is specifically added here to demonstrate the link of each aspect with one or more of the propositions in this thesis. A negative (-/-) sign indicates that 'ticks' on the right side of the table (somewhat more, much more) show that the student experiences oppose that proposition. For example, the responses for the dimension "Requiring mental effort" indicate that these oppose proposition 10.

Dimension	Much less	Somewhat less	Same	Somewhat more	Much more	Relevant Propositions
Encouraging creativity			X	XX	XX	1
Providing direction for finding inspiration				XX	XX	2
Requiring mental effort				XXX	XX	-/- 10
Encouraging deep/ complete (issue) analysis		XX			XXX	2
Rewarding				XXX	XX	8
Generating high quality results		X		XXX	X	5
Overwhelming (much information to process)	X			X	XXX	-/- 8
Confusing (what information to use)		XX		X	XX	-/- 8
Having an Inclusive result				XX	XXX	6
Resulting in a universal outcome			X	XXX	X	-/- 1
Having a rich result				XXXX	X	2
Leading to results that are easy to adapt to different circumstances				XXXX	X	4, 6
Allowing for co-evolution between problem and solution				XXX	XX	2
Revealing (hidden) connections between information-bits				X	XXXX	2
Workable process	X	XX		X	X	8
Common sense process			XXX	XX		8

Table 4.2 Replies to closed part of the evaluation form

The actual responses to the open questions can be found in Appendix A4.5. The interpretation of the responses to the open questions was primarily used to enrich the direct (factual, numerical) pattern of responses to the closed questions. The interpretation of the responses in part C of this case study is intersubjective, i.e., based on the dialogue between the student and the researcher to verify correct understanding of these responses. Because the source data is directly accessible the reader can assess the validity of the interpretation.

Because the students in this case study chose to use CVD voluntarily in theory they might be somewhat positively biased. However, there was no incentive for them to evaluate their experience more positively or negatively than it actually had been. Neither strategy would have benefits, in terms of grading or otherwise. In other words, since there are no signs that indicate the contrary we may assume that their evaluation responses reflect their actual experience.

The responses represent the best available collected experiences of deep cases (at least six months per design assignment).

C. Findings related to the propositions

The main findings in terms of the propositions (3.6.2) are:

For proposition 1: unanticipated insights are likely to be created in a shared design space

- The scores on "encouraging creativity" tend towards a positive assessment compared to other methods. The scores on the aspect of "resulting in a universal outcome" do suggest that the outcomes in the perception of the students might be characterised as being a compromise.
- Several choices for the product (architectures) or even target groups would, by their own admission and reflection, not have occurred without CVD.
- The use of more different perspectives than otherwise would have been the case early in the design process was mostly considered as positive. A 'negative' side note, also relevant for proposition 8, was that the use of many different perspectives also made it more difficult to know for the designer when to stop using these perspectives. The desirability to use more perspectives than just the one of the designer can reduce bias but when does the marginal added value start to go down?
- In particular when not immersing in one of the contexts, or with little information available because of other reasons, the insights from that context can be or feel somewhat shallow. This can result in a gap in the depth of the insights between contexts or settling for the more

shallow level for the other contexts as well. Such an occurrence might account for the very different scores on “encouraging deep/ complete (issue) analysis”.

For proposition 2: a rich design space leads to well-informed choices

- The scores on the aspects “providing direction”, “deeper analysis”, “rich result”, “co-evolution” and “revealing (hidden) connections” support the notion that using CVD creates more richness in the sourcing, analysis, choices and potentially the eventual results.
- The qualitative comments, i.e., answers to the open questions, indicate a more complete and better informed overview, for example when the designers compared their research to similar cases from the past. In particular the ‘forced’ interaction between insights is valued.
- By being encouraged to be open minded at the start, this attitude can help to also stay open minded during later stages of the design process, e.g. to overcome barriers and switch directions when necessary.
- For some students the broadness of gathered intelligence did cause some more confusion compared to what they were used to, for others it did not. The confusion seems to be mostly about assessing the value of different insights and the point in the process to take a next step.
- While the richness of the design space seems to be recognised by the students, it is not always fully clear whether and/or how they relate this to their eventual design choices.

For proposition 3: a shared understanding of the concept of richness can help to grasp a complex design challenge

- The students seem to have a rather intuitive grasp of richness, and a few mentioned specifically what they understood this to be. The evaluations did not provide specific information on whether having a clearer more shared definition would be helpful to grasp a complex design challenge.

For proposition 4: considering multiple use cases contributes to an architecture mind-set

- The scores on the adaptability-aspect indicate a positive assessment for the relevance of an architecture as opposed to a single product.
- Without a multi-contextual focus, there would have been little to no attention for the potential added value of a multi-context business model, and therefore overarching architecture. One student mentioned that such attention is more likely to accelerate transitions.
- A multi-context approach was found to be potentially helpful when creating an overarching narrative, with specific contextual focal points.

For proposition 5: design outcomes following a CVD-approach potentially have a higher performance

- The perceived quality by the students of the end results is higher than they imagined would have been the case without CVD. In one case the student specifically judged the result with CVD being "better" than via a double diamond process model. There was no possibility for a formal assessment of this because the students worked on assignments with unique results, i.e. there was no real-life alternative result to compare it with quality-wise.

For proposition 6: multi-contextual design spaces are likely to result in (more) inclusive results

- The perceived "inclusiveness" by the students of the end results is higher than they imagined would have been the case without CVD. The "universal outcome", which is not the same, was perceived as equal or better. A universal outcome is not the main aim of using CVD. The higher scores on "adaptability of results" does however indicate a positive assessment with regards to using CVD.
- In the qualitative comments several students mentioned the higher inclusiveness even while not specifically asked to do so.
- CVD was mentioned as the only method the students knew that *explicitly* guides designers to source information from multiple contexts or potential use-cases and thereby potential target-audiences early on, and let the results in the form of insights actively interact instead of implicitly 'linger'.

For proposition 8: willingness by design engineers to embrace complexity implies not demanding or needing detailed instructions

- The scores on "rewarding", "overwhelming", "confusing" and "workable process" confirm the expectation that using CVD requires quite more mental effort. By their admission, this may feel a little daunting but in the end does also lead to a more rewarding feeling.
- One student specifically mentioned that the process was in fact less overwhelming, in particular because the CVD approach encourages to frame the information that is gathered in the form of insights. This form provides an implicit level of overview that he did not (explicitly) encounter in some other methods.
- The fact that it is still considered to make "common sense" in at least equal measure with other methods indicates that there seems to be a case to use CVD in the right circumstances.
- With multiple contexts being such a pivotal element of the approach, some students experienced problems deciding what these contexts should be, apart from basing this on very practical considerations. More guidance would have been welcome in that respect.

- The initial broadness of sourcing insights (divergence) is mostly considered as positive but does seem to require some form of guidance when to stop, i.e. take stock (revergence) and move forward with more focus (convergence). While true for any design process, CVD may not make this decision on timing easier. The approach does however indicate the presence of these moments in the form of the shared design space (revergence) and construction of the product architecture (convergence).
- The use of CVD in the experience of the students in this case study encourages rather than blocks use of more specific design tools. Choosing how to apply the tools exactly, i.e. ascertaining the influence of information coming from multiple sets of requirements, can require extra mental effort.
- At least one student explicitly mentions the difficulty of the perception of having to work with a moving target, more so than with other methods.

For proposition 10: if decision makers think in terms of time-to-markets, they may allow a higher initial effort to include a wider diversity of requirements

- The score on “mental effort” could be an indication in support of the expectation that for managers who use traditional metrics that focus on initial effort, CVD is a daunting prospect.
- In the qualitative comments the notion of having more difficulty to choose because of the higher number of insights, ideas and possible directions is conveyed by several students.
- Because of the broader sourcing and open minded attitude, points in the process that would normally create a barrier, like discovering unfeasibility of a chosen design direction, can be more easily side-stepped, thereby saving time as well, even preventing having to go back entire stages.
- The metaphor of a moving target (see above) might especially relevant to explain potential fear with certainty-seeking managers.

4.3 From findings to insights

The step from the findings on case-level to overarching insights per proposition is not a deductive analytical one. This step by definition requires creative and reflective inductive interpretation by the researcher, which again like in the precious steps was scrutinised through various verbal and written interactions with a stakeholders in this research (design experts, colleagues at conferences, peer reviewers of papers), as explained in the research approach and visualised in figure 2.4. The sources for this stakeholder interaction, i.e., the case-specific findings, and its results, i.e., the overarching insights per proposition based on these findings, are fully available to the reader. Therefore anyone can assess for themselves whether they consider the results of this stakeholder interaction, i.e. the overarching insights, to be acceptable. This is not to say that anyone would have necessarily made the exact same translation. This is discussed further in section 6.3, the methodological reflection.

As one remark to take into account that applies to all propositions: in the broad cases the time that the design students had available for their assignments was limited, in the order of magnitude of a few days at most. While this might influence their perception of the value of CVD, i.e. introduce a negative bias, it is exactly why these cases have also been included in the selection. By intentionally including different *types* of cases the results can feed into a productive discussion whether there are conditions that are more conducive for CVD to be, and/or be perceived as, an appropriate design approach.

Proposition 1: unanticipated insights are likely to be created in a shared design space

- Insight 1.1: The deep case studies all demonstrated that a shared design space with inputs from multiple use-cases a/o contexts triggered thinking that was valuable for next steps in the design process. In many instances when that thinking resulted in unexpected insights these would not have been likely without the shared design space.
- Insight 1.2: Practitioner feedback for case #3 (section 4.2.1) explicitly confirmed that in practice the focus is mostly on one context and considerations for other contexts are often not made or even avoided. The practitioners in question stated that the latter would in fact be a good idea.
- Insight 1.3: A shared design space, explicitly fed from multiple use-cases, allows for easy identification of connections and patterns.
- Insight 1.4: In the stated experience of most design students in the deep case studies, the use of a shared design space has complementary value and gives direction to decide how to include other design methods and tools from their arsenal, rather than that it excludes the use of these methods and tools.

Proposition 2: a rich design space leads to well-informed choices

- Insight 2.1: The deep case studies showed that in particular by connecting requirements from different contexts, choices that the students made about what to include in the design concepts and how, were well informed when using CVD.

- Insight 2.2: The broad case studies yielded positive as well as negative associations in the perception of students in terms of being better informed when they made their design choices when using CVD vs not using CVD. Available time seems to be an important factor that can tip the odds in the favour of using the CVD-approach.
- Insight 2.3: For some students the overwhelming nature of the broadness of requirements in a CVD-stimulated shared design space did not work well, in particular in the broad cases where time was limited. They experienced the abundance of potential requirements as a disturbing factor to help them in taking decisions.

Proposition 3: a shared understanding of the concept of richness can help to grasp a complex design challenge.

- Insight 3.1 Design experts can assess the notion of richness intuitively but do not necessarily use the same interpretation. This was demonstrated to create confusion when discussing it.
- Insight 3.2: As alternative, a three-part working definition of richness that has been tested – to be discussed in section 4.4.1 - turned out to be workable in terms of arriving at an assessment of richness that represents a level of shared understanding.
- Insight 3.3: Assessment of richness seems to be more suitable to apply to design outcomes that are themselves more complex like sets of insights or design concepts, but less so when applied to singular intermediate design process results like single contextual insights. However, as also to be discussed in 4.4.1, the latter may provide an unavoidable route to the former.
- Insight 3.4: Whether a shared understanding of richness, by using the same definition, has added value in discussions amongst designers has not yet been investigated in practice. The idea of such a discussion is that a 'low richness-score', e.g., determined as will be presented in section 4.4.1, might provide an 'early warning' that results in a design process thus far do not reflect the complexity of the challenge, and therefore it is too early to move towards a next stage.

Proposition 4: considering multiple use cases contributes to an architecture-mindset

- Insight 4.1: The types of patterns and connections that are created when using a multi-context approach in most instances did encourage creation of design concepts that represent a product architecture rather than a single (optimised) product.
- Insight 4.2: An 'architecture-mindset' is likely to be more encouraged when business model considerations are included in the design assignment.

- Insight 4.3: Seriously considering a near future of multiple contexts can justify an architecture-mindset as opposed to a single product-based one even if the first implementation phase does not concern multiple contexts.
- Insight 4.4: Even when not explicitly thinking in terms of a product architecture, bringing together insights from multiple use cases did encourage design choices that can – if so desired – be part of an adaptive architecture, e.g., be turned into an optional feature.

Proposition 5: design outcomes that are created with a CVD-approach (i.e., systematic variation before the design task is set) potentially have higher performance than comparative alternatives without the CVD approach

- Insight 5.1: Based on both deep and broad case studies, the quality of the results coming from a CVD-driven process are mostly perceived as higher by design students and principals than if the same design challenge was taken on without using CVD as overarching mode of thinking.
- Insight 5.2: The exact way how "performance" is measured in each case study obviously varies but as case studies have demonstrated, as long as this performance is compared within the same domain (e.g. clean cooking) a comparative statement can be made on the performance of different designs.
- Insight 5.3: A broader interpretation of "fitness for use" (Juran and Gryna, 1980), e.g., "fitness for multiple target groups", is likely to boost the desirability of an intentional multi-context approach.

Proposition 6: multi-contextual design spaces are likely to result in (more) inclusive results

- Insight 6.1: The perceived inclusiveness of results when using CVD is higher. Both students and practitioners have recognised this, even for small assignments.
- Insight 6.2: As far as possible to assess based on the information in the case studies, the actual inclusiveness with regards to the fit of a design result with requirements from multiple end-user groups is so far found to be higher than for the design result of comparable cases without a multi-context approach.
- Insight 6.3: Inclusiveness occurs on two levels, process (stakeholders) and contents (that are relevant for a range of disenfranchised beneficiaries). For inclusiveness on the process-level to truly materialise the designer needs to pay close attention to ensuring the diversity of stakeholders across the use-cases. I.e. different use-cases are likely to require involvement of different types of stakeholders. Use of CVD does not explicitly enforce use-cases based stakeholder diversity, but it would be a logical consequence (Ref #9).

- Insight 6.4: As has been argued in Ref #9, to create appeal for development practitioners and funders to use a multi-context product development approach, linking it with the – framing of – SDGs (Sustainable Development Goals) might be conducive. In particular framing it to show how more inclusive positive societal impact can be achieved.
- Insight 6.5: the level of actual inclusiveness of CVD-fuelled design process results in practice, i.e. after implementation and during market adoption, has not been tested because the case studies did not reach that stage yet.

Proposition 7: to perform well in a complex design challenge, the (business) environment has to allow a high level of unpredictability of the outcome.

- Insight 7.1: If in the eyes of the responsible manager it is clear that the outcome of the design process will not be a complex product itself, unpredictability of the exact outcome might be more acceptable for these managers.
- Insight 7.2: (managerial) Willingness to accept unpredictability of design process outcomes due to a multi-contextual approach is likely to be higher if a positive influence is expected on the viability of the business case, both for initial product launch and scaling.
- Insight 7.3: If designers or principals have a preconceived notion of the outcome of the design process, using CVD is mostly considered to represent an unnecessary use of resources and the designers are not likely to receive support to spend these resources.
- Insight 7.4: “Unpredictability” might be considered less of a problem and more of a fact of life if managers are sensitised by regular contact across contextual borders.

Proposition 8: willingness by design engineers to embrace complexity implies not demanding or needing detailed instructions.

- Insight 8.1: (junior) Design engineers that willingly choose to use a CVD-approach in general seem to have a base attitude that prevents them from panicking about lack of detailed instructions.
- Insight 8.2: A relatively crucial factor for designers in not demanding detailed instructions is to have a reasonable period of time available to execute the design task. That does not mean there should be no planning or a form of time boxing.
- Insight 8.3: In absence of a reasonable period of time being available, the majority but not all junior design engineers tend to give the process uncertainty a try. In most cases this yields positive results in terms of how they experience the process. Discovering by Doing seems to beat Discovering by Thinking, but it is all part of the interaction between Art and Science.

- Insight 8.4: The case studies contribute to an emerging feeling that effective guidance might have to include timely expectation management by supervisors of the design process with regards to the complementarity of CVD as overall mindset. The use of CVD allows ample room to use other methods and tools during the entire process.
- Insight 8.5: As suggested by several junior design engineers in the deep as well as broad case studies, an effective form of guidance might be to supervise in a way that allows them to recognise the moment when to stop sourcing in insights from multiple contexts and continue with next steps, revergence and convergence.
- Insight 8.6: Receiving help with determining which use cases to consider, decide to include and how to distinguish them in the first place is likely to be a desirable form of support that is in fact currently lacking.

Proposition 9: willingness to embrace external complexity is influenced by fear of internal complexity, i.e. fear of the design process resulting in a complex high-tech product.

- Insight 9.1: As an extension of insight 7.1, non-design practitioners (also if not in a management position) seem to have a (latent) fear that allowing a high level of complexity and diversity of requirements can only result in a complex product. Examples and cross-contextual discussion that this is not the default case may be an effective way to enhance the appeal of this approach.
- Insight 9.2: To prevent the perception that a design process that acknowledges complexity by definition results in a complex product, it can help to clarify that the overall programme of requirements for the result is not just a tally of all individual requirements from each context, but -through hierarchical decomposition- is likely to capture synergies that build on interrelations between requirements.
- Insight 9.3: To get more acceptance for the use of CVD it may be useful to specify that by taking interrelations (aspect-systems) specifically into account, the design optimises these relations rather than specific components (sub-systems).
- Insight 9.4: Similar to Insight 8.2, the general willingness to allow more complexity in the process seems to be higher if more time is available for the design process, which allows the design engineer to consider choices better so they can in fact create non overly-complex products but also avoid overly simplistic choices.

Proposition 10: if decision makers think in terms of time-to-market**s** (plural)**,** they may allow a higher initial effort to include a wider diversity of requirements.

- Insight 10.1: There is some indication that decision makers who anticipate the relevance of multiple markets may be willing to allow more resources to be used in the first stages.
- Insight 10.2: The case studies do not provide explicit results with regards to development of metrics to support decision makers how much extra effort to allow in the first stage(s) of the design process.
- Insight 10.3: Thinking in time-to-markets is likely to encourage a mindset that reduces the risk of efficiency-driven single-market-optimisation and is thereby conducive for CVD-thinking.
- Insight 10.4: Metrics that express overall diversity of target groups, which can only be achieved by looking holistically instead of geography-based, may be conducive to allow more initial resources to be allocated. The case studies did not extend far enough to explicitly verify this.

4.4 Taking stock

The research plan is to move directly from the insights, as presented in 4.3, to the extensive reflection on these insights, in relation to the propositions, in chapter 5. Upon some scrutiny, it was deemed desirable to include an intermediate step in the reporting of the research process in order for the required mental effort by the reader to move from the empirical results (4.3) to their reflection (chapter 5 and on) to be not too large. Therefore this section offers a first quick glance at what the research and in particular the cases have given back when viewed through the main angles of the research as presented in section 2.1: *Design Engineering arsenal* and *Empirical framing* (including education).

All instances in this section where a case is referred to (#1, #2 etc), the ID-number is the one from the list of cases, table 4.3, not the longlist.

4.4.1 Design engineering arsenal

General impression of the value of the approach

Because this thesis represents an exploration which came to be centred around the approach called CVD, it made sense to try and capture how that approach might be different or add value compared with existing design approaches. Based on the tentative results as conveyed by the empirical insights so far (section 4.3), the approach seems to have value for design engineers, with much still to be interpreted and discussed in the next chapter. Nevertheless, if after that discussion this general (for now tentative) conclusion still holds, next steps might focus more on the question “in *which circumstances* is CVD an appropriate approach and how can the potential value be *unleashed* in the best way?”.

Key construct of richness: can it be assessed?

Some specific attention is justified for the notion and key construct that obviously did already exist as a notion but has received a place in the spotlight in this research: richness. Richness can be considered related to design spaces and in relation to design results. Both enjoy some intuitive understanding, presumably more so by experienced than by novice designers. Several cases in this chapter and Appendix A4.3, like case #1, #2, #4 and #5 demonstrated that they too have some intuitive grasp of this concept. The proposition however encouraged to explore whether this intuitive grasp suffices in the face of complexity.

As discussed in section 3.5.3.3 and in case #1, quite different interpretations of richness exist. These interpretations don't necessarily collide but do not all point in the same direction. The noise and confusion that is thus created in discussions may unnecessarily distract. This while discussing the richness, e.g. of empirical results or a design outcome, in itself can already result in more than enough heated debate. The debate itself is not the bad point.

There is more to this line of thinking: if we accept the premise that the notion of richness of a (n intermediate) result in the design process is relevant when discussing complexity, and we accept that the design task and design space need to reflect this richness, then it makes sense that we need to have a shared understanding of this richness. Such a shared understanding could help to determine, as a group instead of an individual, whether the *complexity of the design challenge has been captured*, in a proper problem analysis and early results in the design process. If the agreement, i.e. explicit shared understanding, would be that the richness is still low, that would be an 'early' warning that the complexity of the design task has not yet been captured in the results thus far.

Case #2 (in particular part C of the case description in Appendix A4.3, and results in A4.4) contained a trial into the feasibility of such a shared understanding. Below, three main findings with regards to that trial are shared. In section 5.2 these findings will be related to the insights and reflected upon in more detail to assess their meaning for this research.

1) The three-part defined construct that was tested in case #2 was demonstrated to be workable and value adding, in the sense that designers could assess the overall richness of a unit (in this case "insights") based on three components of richness, instead of giving just one overall mark, as happened in case #1. Therefore much more nuance was possible to be included in the assessment scores in case #2. When the dust of that nuance had settled, a clear picture emerged about the intersubjectively perceived differences in richness between the different assessed units, i.e., order emerged out of the chaos and this order revealed that the level of richness of the set of shared insights, as opposed to the sets of mono-context insights, was notably higher.

Framed in line with the above: in a comparative sense the richness of the set of shared insights was assessed to be higher. We might interpret this such that the actual real-life complexity had been captured better by the shared insights and thereby in all likelihood resulted in a design direction that (better) matches the requirements from this complex reality. The fact that the performance of the gasifier stove based on these insights was high (see case #2) supports this statement.

2) This way of assessment might work in particular for assessment units that themselves are complex, like “set of insights” or design concepts. If units are assessed that have relatively little complexity, like single insights, it seems that the nuance that is provided by a three-part working definition is too abundant and may be confusing rather than helpful. However, as was shown, it may need to be necessary to go through that chaotic step, i.e., assessing individual insights, to enable the emergence of order, actual patterns on a higher level.

3) Whether such a shared understanding then contributes to a *fruitful dialogue* on the extent to which the complexity of the design challenge has been captured has fallen beyond the scope of the research so far. The positive performance of the design result based on the set of insights with the highest richness score in case #2 is notable but not to the point in this case. The assessment occurred afterwards and not during the design process, so was not a part of the dialogue amongst designers and between designers and principal.

4.4.2 Empirical framing

Management considerations

One area to pay attention to is the inclusion of, or formulated better, alignment between management and design considerations. As far as can be stated based on the cases, there seems to be a level of willingness with design engineers to go with the flow and *embrace connections* instead of simplifying the scope of the problem to be addressed and the design task to match and giving in to fear before the journey has even started. Whether this is a likely attitude for managers who have to deal more specifically with aspects like control, accountability, uncertainty and strategic consequences, is less evident, at this stage of the research.

Based on this research, it is however now possible to explore this a little more, in free-form for now and more formally in the next chapters. What the cases reveal is a possible way to reduce potential fear with managers who seek to *control and thereby reduce* uncertainty and unpredictability with regards to outcomes, namely to *show real-life examples* how acknowledging complexity in the design task, even when it makes a design outcome 'complex' does not necessarily need to be a bad thing because that reflects reality better. The cases contain such examples:

- In case #1, the intentional joint consideration of very different contexts resulted in a base architecture that by all standards can be considered not only more adaptive but also simpler (separate hardware device from software layer instead of integrating them).
- In case #2, the consideration of urban and rural contexts did pose different requirements, but also besides a well-performing stove created new opportunities for a superior business model that explicitly makes use of connecting the contexts.
- In case #3, the differences in the requirements from the different contexts invoked a level of thinking that encouraged creative design choices to materialise, without the stove becoming more complex itself.
- In deep case studies, students at times did express some difficulty with keeping an overview but once undeterred also saw the potential and the elegance of the images (i.e., clear leading thoughts for eventual design choices) that emerged from that initially overwhelming collection of rich data.
- Vice versa, case #7 demonstrated how not considering different use cases in time if not blocked then at least greatly complicated a viable business case, even though a first pilot seemed to indicate otherwise.

These are just a few examples that might help to illustrate how aiming to be fully in control – in advance - of the outcome is not necessarily preferable. Acknowledging real-life complexity on the other hand does not need to have adverse effects, as long as you allow room for some level of uncertainty in your management system: planning is still indispensable, but now based on a plan that is based on real-life insights.

An emerging notion on these aspects of uncertainty and unpredictability: there might be a difference between the short and the longer term (scaling phase). Generally speaking, with a regular approach (R1.0, figure 2.2), there is low unpredictability about the design outcome on the short term because of the fixed and relatively confined design task, but the uncertainty for the longer term (scaling potential) is higher because there is no knowledge on the match of the design outcome with requirements from other contexts. With CVD this is roughly the other way around: unpredictability for managers about the short term, i.e. what exactly will come out of the design process following the design task, is higher but once that design outcome is clear there is more likelihood, or 'less uncertainty', about the *scaling potential*, in terms of its adaptiveness to different scenarios. This short/long term distinction in framing consequences to managers might be an interesting angle to explore more deeply in next steps.

The cases and publications like Ref. #8 provided some emerging clues, but not yet provide conclusive results how better alignment might take place between the 'technical' design engineering process and the management processes that govern it. In other words, how might decisions on manoeuvring space for design engineers (how broad and far are they allowed to look and when) be brought in line with practical conditions (budget, and timelines and external network to be included) that are important parts of the "decision space" within which managers have to operate.

An important lesson that seems to have emerged from the cases, is that a design process that revolves around adaptability (of the process and results) requires a management approach to match for the benefits to materialise. What this should mean in practice is a relevant area for further exploration. Ideally such further research would need to more explicitly include interaction with managers. Part of that research line could be to investigate how -framing of- the distinction between short and longer term with regards to 'certainty' for managers might affect resource allocation at the start.

Design engineering education considerations

In terms of guidance for MSc-level design engineers themselves it apparently is not a matter of them needing, or not, detailed prescriptive instructions in an absolute sense. Based on all evaluations and comments the discussion might need to be focused more on the *types* of guidance, and their timing. It also does appear to be important to provide clarity on the Why of the approach: why might it be relevant to consider and what is the purpose, what is the benefit, and for whom. Next, there seems to be a real need to clarify that use of CVD does not exclude other methods and tools Some students have autonomously stated this themselves but since it was not explicitly conveyed to the design engineers who were involved in the case studies some got confused on this matter.

Extending the point above, in terms of the matter of the desirability or not, of prescriptive instructions ("What to do exactly"), it could be observed during execution of the cases that practical questions were raised by students several times. For example: how does "systematic variation" take place *exactly* (where to start), *how does* the design characteristic of "hierarchical decomposition in aspect systems" *help me as a design engineer*, *how many* contexts to choose, *what separates* one context from another, how – *in practical terms* – can you bring insights from multiple contexts together, *what to do* to prevent endless divergence, *what actions to take* to 'ensure' that working with contradictory requirements results in a smarter design choice instead of a watery compromise?

All of these questions have merit, and they do seem to point at some demand for an instruction-level manual, but the question is, when. A workable harmony might need to be found between on the one hand trying to answer such questions upfront, before they are even asked, e.g. by means of a manual, and providing some thinking principles and examples from practice and leave the *real decisions* of What to do to and How to do it to the design engineers themselves. This point will obviously return in the next chapters.

Chapter 5

Chapter 5: Empirical results vs Propositions: patterns and implications

The empirical findings and insights as presented in the previous chapter provide answers and raise new curious questions, as can be expected when conducting inductive exploratory research is performed.

In section 5.1 the reflection on the empirical results starts with an overview that shows the extent to which propositions (section 3.6.2) were mostly supported by the insights (section 4.3), opposed or whether the insights rather reflect that the case studies revealed the need for "evolved thinking" on the topic that was touched in a proposition. The resulting *observable* patterns are discussed in 5.2.1. This serves as additional input for a thorough discussion in 5.2.2 of the empirical results compared to the literature from chapters 2 and 3 and additional sources where necessary.

This is followed in section 5.3 by a discussion how these considerations affect the conceptualisation earlier in the thesis, i.e. CVD 1.0, as visualised in figure 3.1, and what improvement points might therefore be in order (5.4). All of this is then taken to the next level in the final chapter 6 in the form of final conclusions with regards to the Main Research Question (MRQ) including an upgraded conceptualisation of CVD 2.0, the contribution to academic literature, an evaluation of the use of the research methods and suggested next steps for research and practitioners.

5.1 Overview of empirical insights in relation to propositions

The table below shows the overview of the numbered insights as they were presented in section 4.3. Each insight is placed in one of the columns, indicating whether it largely supports (left column) or largely opposes (middle column) the proposition, or alternatively that the insight mainly represents food for evolved thinking with regards to that proposition (last column).

Proposition (shortened)	Insights in support of	Insights opposing	Insights highlighting need for evolved thinking
1: Shared design space yields unanticipated insights	1.1, 1.2, 1.3		1.4
2: Rich conceptual design space results in well-informed choices	2.1	2.3	2.2
3: Shared understanding of richness helps to grasp design complexity	3.1, 3.2		3.3, 3.4
4: Architecture-thinking is stimulated by contexts that represent a level of diversity	4.1, 4.3, 4.4		4.2
5: Systematic variation before design task enhances quality of outcomes	5.1, 5.2		5.3
6: Multi-context approach enhances inclusiveness	6.1, 6.2	6.5	6.3, 6.4
7: Valuation of design result benefits from accepting a level of unpredictability	7.2, 7.3		7.1, 7.4
8: Embracing complexity goes against need for detailed instructions	8.1, 8.3	8.6	8.2, 8.4, 8.5
9: Fear of complex products can hamper use of multi-context approach	9.1, 9.2		9.3, 9.4
10: Time-to-markets should replace time-to-market as important metric	10.3	10.2	10.1, 10.4
Number of insights per option in top row	20	4	17

Table 5.1 Overview of the empirical insights in relation to the propositions

As one overarching observation, it can be seen that the insights are 'constructively scattered' in terms of supporting, opposing or requiring evolved thinking, in relation to the propositions. In more detail: a sizable number of insights indicate that there is some room for development (final column) in terms of investigating and/or reframing proposition areas. This is in fact a result that can be expected when conducting exploratory, inductive research. The number of insights in the left column (support propositions) at the same time suggests that the propositions do seem to strike a chord with reality, while not representing it perfectly yet (middle column).

Note that the numbers of insights in each cell by itself do not suggest any mathematical precision of the placement process. More importantly the numbers in the last row of table 5.1 should not be considered as real numerical totals because these numbers represent basically a tally of 'apples and grapes' (wrong expression-reference intended). More concretely, a large difference is likely to exist between insights in terms of the *extent* to which they belong in the column they were placed in, and some insights might be of greater *significance* than others. These distinctions are not made here, but the reality is there nevertheless. The pattern of how the insights *are* located in the table therefore merely provides a first glance of the empirical results in relation to the propositions. A substantially higher number of insights in a particular cell, and in the totalisation row is not more than a rough indication of the extent of support, opposition or ambivalence. Deeper qualitative interpretation of that first-glance result follows in the next section.

5.2 Discussing empirical results

In this section the straightforward patterns in table 5.1 are addressed in 5.2.1, i.e. a brief discussion on how the insights are located, per proposition and briefly what the pattern in each row seems to imply. The empirical results are interpreted and reflected on in depth in terms of what they mean, in the second part of this section (5.2.2) with extensive discussion in light of the academic literature.

5.2.1 Observable patterns of insights in light of the propositions

The observable patterns that can be seen in table 5.1 in section 5.1 are discussed below. The main starting point for each discussion are the insights in each column for a proposition. The discussion below is structured according to the propositions that are related to each other and to that end follows the main angles as presented in section 2.1.3: *Design engineering arsenal* and *Empirical framing*, the latter divided in matters pertaining to *Scale/ sustainability/ inclusiveness/ management* and *Design engineering education*. Particularly in this sub-section 5.2.1 keep in mind the remark at the end of section 5.1: numbers cannot simply be added but they can be used as 'first glance' input for reflection. The discussion in this section represents the one that was announced in chapter 2 regarding assessing the degree of plausibility of the propositions, in light of the results of the empirical research.

5.2.1.1 Propositions focusing on Design engineering arsenal

In particular related to propositions 1, 4 and 5, the locations of the majority of the insights in the table in the left column, suggest that the empirical experiences are mostly in support of these propositions: *when applying systematic variation before the design task*, the keystone of CVD, this has a *positive influence on unexpected insights* (*prop* 1), *using an architecture-mindset* (*prop* 4), *and potentially achieving high performance and quality* (*prop* 5).

In short this means that the cases have provided *a level of* empirical support that CVD can constitute value for a design engineer. At the same time the presence insights for each proposition in the right column indicates that there is also still room for mastering these proposition areas. This is the type of result that should be expected when investigating something novel in practice.

When looking at the results for proposition 2, purely in the sense of a loose first glance, a balance exists between support (2.1), opposition (2.3) and suggesting the desirability of reframing the topics (2.2). This pattern suggests that the area that is covered by this proposition, *well-informed choices coming from a rich design space*, simply needs to be investigated further but there seems to be sufficient reason to do so.

In short, for the notions that are addressed in propositions 1, 4, 5 and to a lesser or less evident extent proposition 2, the empirical results are providing a decent level of support for the propositions, with room for further evolution. To make further research in support of this evolution more worthwhile, the main questions that guide this research may therefore have to shift.

Building on proposition 2, the proposition which was *most dedicated* to the key construct of richness was proposition 3. The richness referred to richness of intermediate design results, not of the physical design space.

In practice, as expressed in *insight* 3.1 (and found in case #1), the many different interpretations of richness can create confusion and distraction when discussing whether a result is 'rich or less rich'. This is therefore a finding in support of this proposition. More specifically, when designers, and others, were to discuss the "richness" of a design task, a concept, and later on an actual product, and use different interpretations, the discussion and therefore its outcome runs the risk of being polluted because of that confusion: they may not agree what they (dis)agree on because there is no shared understanding of what they are discussing. The first test with a three-part working definition that would address that problem, as captured in *insight* 3.2, was found to be workable. This is shown in part C of case #2 and the short discussion in section 4.4.1.

With insights 3.1 and 3.2 largely supporting proposition 3, some nuance is provided by insights 3.3 and 3.4. Insight 3.3 demonstrates that if richness is to be assessed, this makes more sense for assessment subjects that themselves are complex, like "set of insights" or design concepts, and much less with simpler assessment subjects like single observations by a designer. The placement of insight 3.4 in the right column in table 5.1 expresses that the question has not been addressed yet whether a shared understanding of richness contributes to a fruitful dialogue on the extent to which the complexity of the design challenge has been captured.

In short, the proposition topic – creating a shared understanding of richness - seems to be both promising as well as not yet fully excavated.

5.2.1.2 Empirical framing: propositions regarding scale, sustainability and management

With regards to the first proposition in the list referring to this angle, proposition 6 on inclusiveness, a somewhat similar pattern can be observed as for proposition 2, namely as a first glance pattern a balance between insights that indicate support (left column) and insights that point at the relevance of reformulating the proposition (last column), with an insight in the opposition (middle) column to complete the picture. As with proposition 2, this pattern suggests that further investigation is required, but there seems a basic relevance to do so.

The pattern of the locations of insights in table 5.1 with regards to propositions 7 and 9 in general terms suggest that there is plausible support (insights for each proposition in the left column) as well as need for more investigation in these proposition areas, i.e. the (fear of) complexity as a factor that can cause management decisions to be overly cautious, i.e. not changing approaches let alone introducing new ones.

Placement of insights 7.2, 7.3, 9.1, 9.2, all in the left column, i.e., supporting the propositions they relate to, suggest a telling pattern. Namely, when an attitude dominates that acknowledges that the outcome of a design process should not be fixed upfront but be adaptable rather than rigid, a positive effect may materialise. In other words, the placement of these insights indicates that the more the outcome is (implicitly) fixed beforehand the higher the fear of complexity is likely to prevent that positive effect.

What does this mean for managers in terms of decisions how much leeway to allow, e.g., how to decide whether a likely increase of early-stage resources is worth it? This topic is mostly covered by proposition 10 and related insights like 2.2 and 8.2. As a rough pattern, the locations of the insights related to this topic, might indicate that these proposition areas should probably be reframed or reconsidered. This can in part be explained by the fact that the cases did not focus much on the aspect of management metrics, so it is not a surprise that insights do not clearly support or oppose the proposition.

5.2.1.3 Empirical framing: Introducing novelty to design engineering students

A diffuse pattern can be observed with regards to placement of insights for proposition 8. The core question raised by that proposition is whether (junior) design engineers need or desire prescriptive instructions when they are presented with something unfamiliar, like in this case early systematic contextual variation and the broader CVD-approach. The placements of insights 8.1 and 8.3 in the left columns support the suggestion that design engineers who value their creativity do not stand around waiting for detailed instructions and have a base attitude of embracing the (extra) challenge. The placement of the other insights in the table however also suggest the relevance of paying more attention to *How* to provide some level of instructions (8.2, 8.4, 8.5), and *When* (8.6).

These nuances seem to imply that attention is necessary to achieve an appropriate mix between spending energy on *letting* design students understand something new and *facilitating* them to find out whether they are able to make that something new their own. The pattern of the results for this proposition also triggers the sensitive question whether all design engineers should strive to master more strategically oriented approaches or not? This is a topic that is addressed further in the next sections.

5.2.2 Discussing empirical results through literature lens

The discussion in section 5.2.1 focused more on the loose *visibly observable patterns* of placement of the insights in table 5.1 than on the in-depth *meanings* of these patterns in light of the literature. This sub-section represents that very step. Since most literature and a part of the arguments are not new by this point, much will look familiar. The structure within this section again follows the three main angles that by now should be familiar to the reader.

5.2.2.1 Design engineering arsenal

Order in ‘chaos’: understanding richness (Proposition 1, 2 and 3)

When referring to complexity, one can easily encounter the observation that “higher level order” emerges from “lower level chaos” (Johnson, 2002) or that finding a pattern in complexity brings meaning to disorder and is therefore an act of creation, not complexification (Laszlo, 1996). One of the clearest instances where this occurred in the cases was the trial of creating a three-part working definition of richness in case #2 and using that to verify whether using a multi-level shared construct could be a good basis for assessment and thereby shared understanding of this notion. Richness was most explicitly mentioned in proposition 3 but also in 1 and 2. The three individual parts of the definition – representing multiple perspectives, encouraging connections and be generative – were not necessarily new, see e.g.,, (Oades-Sese and Esquivel, 2011, Montuori, 2011, Sevaldson, 2009, Bushe, 2013) but had not been explicitly considered in combination like this before. It seems fitting that this explorative but intentionally designed trial on *richness* demonstrated the notion of *order* (= a clear unambiguous conclusion) emerging out of *chaos* (=completely scattered assessment results without a clear pattern) and the whole being actually *different* than the sum of the parts (Koffka, 2013) instead of the more often used formulation *bigger*.

Different might be a more to-the-point framing as well from the point of view that it is not evident upfront which part(s) of the whole picture are in fact the most relevant (Soni and Goodman, 2017).

Having this more specifically articulated notion of richness high on the mental radar seems in line with a general attitude that facilitates thinking in terms of different perspectives and identifying new connections, which seems a good development for design engineers. In line with more general notions like holistic design (Blizzard and Klotz, 2012) and systemic design (Jones, 2014). Thereby it can contribute to the intended sense of a shared understanding between designers, and designers and managers about the complex nature of a design task.

This way of thinking seems to work together well with tools that encourage designers to look broad instead of focusing early. Not just by using frames (Dorst, 2015), but rather by *combining* frames (perspectives) in the same design space to find and feed off new connections (Morin, 2008). Visually oriented tools like Gigamapping (Sevaldson, 2011, Sevaldson, 2017a) demonstrate this and aim amongst others to "tease out unknown unknowns" (oral quote by the same author) like unexpected patterns and (inter)dependencies and do this physically by combining different media (Sevaldson, 2008) and the synthesis in the eventual materialisation (Lindgaard and Wesselius, 2017) in prototypes. This translation from visually oriented overview to a more physically oriented design result may be one of the important roles that designers have and remain indispensable for.

What is also emerging from this discussion is the suggestion that it might serve designers to anchor the notion of richness into their entire thinking when facing complexity.

Creativity required to create an Adaptive Architecture (Propositions 2, 4)

In a way the adaptiveness that the CVD-approach strives for could be seen as a form of "informed generalizability", "generalizable novelty" or even more to the point, "latent functional creativity" (Cropley and Cropley, 2005). In practical terms this means that the process is relevant in relation to the design task *and* allows users to achieve good or even superior creative results when encountering in part unforeseeable future circumstances. The CVD approach with systematic contextual variation *before the design task is set* in addition to variation *within a set design task* which is the norm for a regular design engineering process (Beitz and Pahl, 1992) increases the functional aspect because it uses more intent. The notion of different known situations ("contexts"), i.e. known knowns, is incorporated from the start which helps to imagine specific circumstances, i.e., known unknowns, and possibly also can play to some extent into the unknown unknowns (Snowden and Boone, 2007). Design that anticipates in these ways will not be heads down geared towards one particular manifestation of the problem (Myerson, 2015) followed by mainly reactive incremental adjustments (Norman and Stappers, 2015).

Some examples in the cases where the more intentional versus the more reactive strategy can clearly be seen are:

1. Case #1: Separating a relatively easily adjustable software layer from the hardware device vs. keeping them integrated and modify the entire integrated design based on requirements from use cases that are addressed later.
2. Case #3: Designing a cook stove architecture that takes into account, amongst others, a broad power range, different types of pans and an optional gas hose extension vs. designing a cook stove for one dominant way of cooking and fuel and changing specific elements once new requirements are required for new types of customers.
3. Case #7: Continuing to explore the acceptance/ desirability of business model options to identify necessity for product feature flexibility vs. scaling a successfully validated business model from a pilot as basis, and consider other options later as long as they do not affect the product itself.

With regards to the extra costs and timelines that come with step-by-step reactive design, there are many who argue that the increased use of platform-based products (Martin and Ishii, 2002), artificial intelligence algorithms, additive (3D) and agile manufacturing will decrease such costs (Pearce, 2013) and timelines for changes and allow for lower barriers for entry in any market (De Jong and de Bruijn, 2013) to such an extent that these considerations become irrelevant when working on the initial design. However, even if that would be the case, the case studies have demonstrated and verified the other reason why using more intent, i.e., design, could still be preferable: as the examples suggest, it can result in intrinsically smarter, even more elegant design decisions. While not guaranteed as an outcome, this increases the chance of successful scaling later on by building on a superior initial architecture.

Interestingly, because it seems outside of the direct sphere of vision for industrial designers, using an extent of intentional redundancy is a core characteristic of human communication according to the 'godfather of information science' Claude Shannon (Soni and Goodman, 2017). No redundancy and too much redundancy are both undesirable. Collecting some eventually overlapping information is however in fact useful. Framed more in terms of this thesis, the sweet spot seems to reside at a place where relevance meets diversity. Mastering to cover that sweet spot is the ultimate creative resilience challenge (Soni and Goodman, 2017). While not from within the industrial design domain, the aim to master this sweet spot seems to be very similar to the aim to aim for richness in both conceptual and physical design spaces.

In chapter 3 it was already stated with care that the assumed innate ability of designers to deal well with complexity (Buchanan, 1992, Cross, 2001, Norman, 2010) (Buchanan, 1992, Cross, 2001, Norman, 2010) is not necessarily helped by being shielded from making difficult but necessary choices, for example in the form of a more complex design task. The cases have now indeed shown that *not* relying on universal low-cost "everything is flexible" platforms can surely encourage more imaginative, creative, adaptive design choices, on purpose (Levy, 1994). Allowing such choices to be made still positions the design engineer more centre stage than when "everything" is made customisable. The latter seems flexible but in fact lacks imagination and, perhaps formulated somewhat harshly, thereby degrades the role of the design engineer.

A question of quality (Proposition 5)

As mentioned at the start of section 3.6.2, proposition 5 might be considered as the bridge between the two main angles (design engineering arsenal and empirical framing). As it has been approached until now it is closer related to the first one.

For a long time "quality" was, and still mostly is, defined as "fitness for use" (Juran and Gryna, 1980). There is nothing inherently bad to say about that. In a way it may however hinder a broader view, like for example is encouraged with the promotion of involving different stakeholders (Suen, 2015), cultural diversity (Sardar, 2010), different perspectives (Linstone, 1989, Linstone, 1999), sourcing beyond the edges of your network (Tetlock and Gardner, 2016), multi-sited ethnography (Marcus, 2009, Falzon, 2016, Hine, 2007), the importance of divergence (Cropley and Cropley, 2005). All these notions raise the generative questions: "whose fitness", or "use by whom"? These questions have become more poignant in light of this thesis.

A seemingly easy option is to score the fitness of a design for a number of user groups and then take the average. This would in fact be in line with the definition of richness by (Weick, 2007) who emphasises that a better quality means it is "above average". This perspective however seems to ignore the characteristic of satisficing as explained in section 3.1.5, and instead channels design towards optimising. To combine several of the sources from chapter 3 in one integral paraphrase: optimising in a complex situation can be connotated with a base attitude of *reductionism* (Nelson, 2007), *early simplification* (Backx et al., 2017) and a *desire for control* (Mundy, 2010) instead of generating *unexpected insights* based on *emergent searching* as opposed to solution finding (Dunne and Dougherty, 2012). Satisficing is however not aimed at achieving one overarching averaged "acceptable minimum" (Beitz and Pahl, 1992) but a more diverse range of acceptable parallel minimums that all need to be met, and preferably exceeded.

Once the notion of satisficing is more enthusiastically adopted by the design engineer, the mental step towards redefining quality in a way that respects diversity is a more obvious one. Along the lines of the earlier reference (Juran and Gryna, 1980), it would need to become something like "fitness for multiple use". As the performance assessment in case study #3 demonstrated the overall performance might still outscore an individually optimised design: in that case the actual performance of the CVD-driven prototype was better, as measured with a broad range of 52 *indicators*, than any of the previous versions which had all been optimised for a specific context. The diversity of requirements in the shared design space, apparently fuelled a generative dialogue (Montuori, 2011) in which mutual interdependencies (Thompson, 1967) were actively sought in order to feed off these interconnections (Morin, 2008) to generate ideas for a design that had a positive effect on the entirety of performance indicators.

There is one caveat for such results to be achieved: the design engineers in charge need to sufficiently possess not only the conducive attitude but also the ability to identify emerging patterns, in the form of shared insights, and be able to create a sense of order in the diverse, scattered collection of information snippets that makes up the collective intelligence (Malone et al., 2010).

5.2.2.2 Empirical framing: Scale/ sustainability/ inclusiveness/ management considerations

Informed Inclusiveness (Proposition 6)

In a way, systematic contextual variation is inherently inclusive in a broad sense. If the application area is large scale sustainability issues in non-OECD countries like is indeed the focus in this thesis, then the logical consequence should be that active attention is paid to not just one but to several "disenfranchised groups" (George et al., 2012). In fact, one might even formulate it in the opposite direction: it seems impossible to be truly inclusive if no variation is applied.

By not following the path of scaling mono-context innovations that turn out not to scale as intended (Kaplinsky, 2011, Ubels and Jacobs, 2018, Kersten et al., 2019b), the initial view is almost unavoidably already broader than that single context, and associated main "disenfranchised group". In a way this almost automatic positive relation between the CVD-approach and inclusiveness is promising and connects with the call for a pluralistic outlook by (Stirling, 2008).

It is however important to realise that the approach is not just an invitation to keep extending the scope of the design task, add more cases, include any number of considerations. Adding even one context that refers to another beneficiary group can already invoke much of the positive effects that are intended. The case studies have abundantly demonstrated this. More relevant than the number is emphasising the diversity (Sardar, 2010) and different perspectives that this diversity will bring (Linstone, 1989). This diversity will feed the variation of framing (Paton and Dorst, 2011) that eventually should create more inclusiveness on contents level (result) and encourages inclusiveness on process level as well (Kersten and Diehl, 2015, Kersten et al., 2019b). Of course, there is some dependency on the specific design engineers how well this is done.

In practice, two inclusiveness-scenarios are likely to materialise when it comes to determining the scope of the design task. The first might be called “conscious exclusion” of contexts and potential beneficiary groups, for example because these groups are not “disenfranchised” enough if social impact is a main aim. The other scenario would be to choose the contexts that – on chosen variables – are farthest apart but still have touch points. This scenario might be called “inclusion by proxy” and assumes that when you cover the ends of a range of contexts, as determined by key dimensions to distinguish the contexts, coming up with an architecture that covers (part of) the requirements from the ones in the middle is more likely than when one of the ends of the range is chosen. Final decisions on inclusion are in practice also based on practical criteria like existing network and access to context specific intelligence.

Management under uncertainty, the role of intent and overcoming fear of complexity (Proposition 7, 9)

Much of the literature discussion and practical lens for the case studies revolved around how to deal with uncertainty and unpredictability, and to what extent the management practice of being in control (Mundy, 2010) and setting SMART targets (Doran, 1981, Piskurich, 2015) still holds when facing complex challenges.

One of the dominant paradigms on how to deal with inherent uncertainty (MacIntosh and MacLean, 1999) and unpredictability of complex systems (Kramer and de Smit, 1979) is to reactively feed off whatever reality has in store for us. As discussed before this is also called “muddling through” (Norman and Stappers, 2015) a strategy originally proposed 50 years ago (Lindstrom, 1959). Whereas this does in a way represent the opposite of emphasising full control (Griffin et al., 1998) and does not *explicitly* prohibit using a vision and intent (Ma, 2019), if the (design) strategy is reactive like this, another problem emerges: it becomes bereft of exactly what design engineers should bring to the table, execution by (some level of) intent, i.e. design. The cases have provided a level of support for the statement that working ‘by design’, i.e. with a substantial level of intent and anticipating on multiple scenario’s, can lead to good design choices that *also leave room to play into emerging circumstances*. In other words: a perspective represented by explicitly designing with *intent* as for example demonstrated in the cases, e.g., (Kersten et al., 2016, Kersten et al., 2017b, Diehl et al., 2018),and a shorter term oriented tactic of engaging in *emergent searching* (Dunne and Dougherty, 2012) are not each other’s enemies.

On the other hand, it is certainly conceivable that there are situations that either do justify a focus on control, or indeed are suitable to muddle through in. Derived from the collective experiences of the cases and as introduced in (Kersten et al., 2019a), figure 5.1 below suggests different situations and matching strategies, when we vary between fixed and open results, on the short and long term.

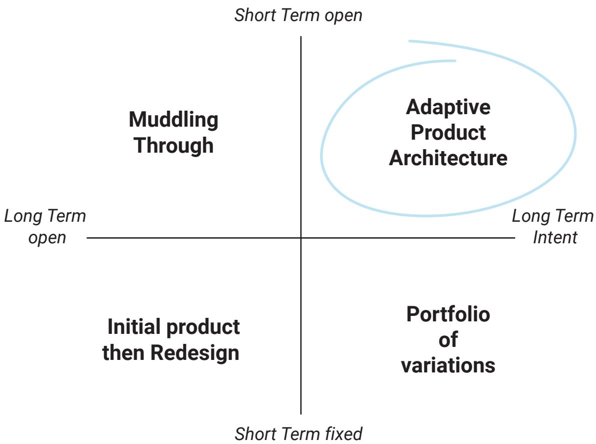


Figure 5.1 Basic strategies based on control-orientation for short and long term

Depending on how the short term result is subject to control-orientation (vertical axis) and the level of intent for the longer term (horizontal axis), four different strategies emerge. The CVD-approach would be consistent with the one in the upper right quadrant. Characteristic elements for each quadrant are for example the *Fear to make a choice that turns out to be wrong* (upper-left quadrant), *Focus on short term control* (lower-left), *Allowing emergence but not passively depending on it* (upper-right), and *Assuming a relatively predictable path* (lower-right). Another notion that fits well in the upper-right quadrant that might resonate with managers is so-called “no-loss” or “no-regret” elements (Bodansky, 2003) as architecture components, i.e., elements that would be relevant in several or even all foreseeable scenarios but do not limit or set the full path forward yet.

All this raises an interesting discussion: on the one hand dealing with complexity does require a level of trial-and-error and “building on what works” (Norman and Stappers, 2015) on the other hand doing so without a decent sense of intent might be perceived less as a design approach and more as a matter of low-level engineering, making something work on a technical level. In management terms, the predictability of the short term outcome is high (and uncertainty low) because a narrow scope of the design task and small steps dominate the process: something is then very likely to work well, technically. This comes however at a cost for the second level of interpretation of “what works”, meaning a more conceptual match with the longer term. In case of a step-by-step approach without much intent, management uncertainty with regards to the longer term remains high, as is the case for evolution (Dennett, 2017). Recognising foreseeable variations requires a level of collective interpretation, for example conceptualised in polycentric innovation (Radjou, 2009). When the CVD-approach is used this collectiveness is first invoked by the systematic variation of general contexts enabling the formulation of shared insights.

This concrete attention for interpreting divergently sought information gives the designer an important role in their relation to general managers, and one that may prevent being used merely as a source for an artist’s impression and as a DIY-expert (Bjögvinsson et al., 2012). The skills associated with the latter roles are important (Cross, 2001, Verganti, 2017, Barth, 2018), but are not necessarily strategic. In an era when designers are increasingly imagined to be able to take on more strategic roles (Calabretta et al., 2016), the focus on the typical aforementioned more physically oriented design skills may be a double edged sword when striving to position designers in these strategic roles (Bjögvinsson et al., 2012). Taking this one step further, it might be a fair and relevant question whether all designers should strive to take strategic roles or whether some should simply focus on being actual designers (Baldassarre et al., 2019).

Much ‘management under uncertainty’ has to do with the base attitude of a manager: circumstances, lack of time, resource constraints and their interrelatedness can always be used as an excuse to simplify. This is not always justified as can be seen in the empirical results. In particular cases #1 (‘developed’- developing country contexts), #2 (urban – rural Vietnam) and #3 (East Africa – West Africa) demonstrate that expanding the scope of the design task, i.e. exhibiting a base attitude of embracing complexity instead of fear-driven reductionism (Nelson, 2007), leads to a more open near future and a more diverse range of requirements, but this did not have to lead to a structure-less mess. The design task is broader, but in fact the landscape within the design task becomes less fuzzy, because there is more direction where to search for relevant information. This addresses the concern of (Zhang and Doll, 2001) that a lack of long term vision can turn the Fuzzy Front End (Reinertsen and Smith, 1991) in an undirected chaos. The design task that incorporates more diversity at the same time provides direction, perhaps even 'certainty' where that diversity can be sourced and that there is a plan for future developments.

While difficult to prove, if we consider the totality of cases, the impression emerges that the base attitude of not being scared by not-knowing (D'Souza and Renner, 2014) and in the humility of admitting this (Montuori, 2012) influences how we perceive "circumstances" in the first place. As the case studies have shown, this base attitude does seem to help to perceive seemingly challenging circumstances not as a lost cause but as all the more reason to engage the situation head-on in all its complexity, instead of going for heads down design (Myerson, 2015). Not just focussing on (geographical) boundaries but choosing key problem dimensions that defy these boundaries might further reduce the risk of heads down design. Paying specific attention to nurturing this base attitude could be considered as a lever for 'system change' (Meadows, 1997). In terms of the leadership that is required this attitude seems to correspond with many factors that are presented as key to being nimble and thereby adaptive: stimulating early discussion instead of decisions, using some fluidity in role division, balancing freedom and control, combining a strategic outlook with actions and overcoming the fear of chaos (Ancona et al., 2019).

As a final point a few words on the importance of contextual intelligence (Khanna, 2014) as driving force for design. An approach that highlights the importance of connections and interdependencies does not deny the relevance and value of a good understanding into "local properties". It adds to that the contemporary reality that these local properties get (more) meaning through their relationship with global properties (Goldstein, 2000).

Management metrics and considerations (Proposition 10)

While some indirect clues have been obtained from the case studies and cases with regards to a necessary shift in thinking about management metrics that facilitate dealing with complexity, the cases were not set up to get to the bottom of this. Most case studies ended directly after the design phase, and sometimes testing, of the prototype, at best.

One of the stated conditions for several principals to participate in the projects to apply the CVD-approach, was their intent to not act immediately on the results perhaps as a way to still keep some control (Mundy, 2010) while being open to experimentation on the short term.

Shifting this to a more serious consideration for looking beyond the short term is likely to occur if metrics that managers are held accountable for also look more at this longer term (McElroy and Van Engelen, 2012). Use of metrics like time-to-markets, diversity of contexts served, end-to-end costs may prove to be an interesting line of future research, perhaps building on the notion of "valuable deceleration". Likewise actively using a metric for inclusiveness of the achieved impact in terms of diverse target groups may very well strike a chord, especially now the SDGs (Assembly, 2014) are gaining importance in the international development discourse.

A notion that was touched upon in chapter 3 and earlier in this section was prospect theory (Tversky and Kahneman, 1991). Basically this theory stipulates that people respond stronger to the option to avert possible losses than possible gains. Although underlying research has seldom been performed when stakes (e.g. financially) were high, it is an interesting notion to explore more explicitly. In this case to intentionally investigate whether decision makers react stronger to framing that implies "averting a possible loss if you don't do X" than "encouraging a potential gain/ benefit if you do X".

All in all the whole area of alignment between design and management considerations, including adoption of principles for complex adaptive systems (Eisenhardt and Piezunka, 2011, Iñigo and Albareda, 2016, Kersten et al., 2019a) is one that deserves further exploration.

5.2.2.3 Empirical framing: Design engineering education

Instructing design engineers: Why and How, not What (Proposition 8)

As has by now become quite apparent, the statement that design engineers by nature deal well with complexity in design challenges (Cross, 2001, Nelson, 2007, Norman, 2010) may be fuelled more by wishful thinking than reality, or alternatively is based on witnessing very expert designers. As mentioned, it may even be an interesting question to ask whether all people that are called designers *should* deal with these types of problems, or whether some should not focus on the more traditional design skills, e.g., prototyping, physical properties, aesthetics, if that is where their passion lies (Baldassarre et al., 2019). The latter is somewhat in line with outcomes of research (Oraklibel et al., 2018) on the limited increase in competence of design students during their education years with regards to *divergence* (in particular actively sourcing in different perspectives) and *originality* (combining these into something novel) as opposed to a clear increase in mastering *usefulness* and *optimising of one solution.*

The case studies, including the broad ones like #4 and #6, have shown that a substantial portion of final year MSc-level students working on real-life assignments did not shy away from facing some complexity. The question is to what extent and in which way they should be supported, or guided both in terms of recognising and applying typical design skills (Barth, 2018, Verganti, 2017, Sevaldson, 2011) as well as developing skills to become indispensable strategic partners for others (Gaziulusoy and Ryan, 2017). The latter under the assumption that they may not want to settle for becoming the visualisers of strategic visions of others (Bjögvinsson et al., 2012). As suggested not all designers may or even should have that ambition (Baldassarre et al., 2019).

The main overarching pattern in the case studies shows that even the ambitious students would have appreciated a little more guidance than they in reality did receive. However, as discussed, that guidance should be focused on the very start of the design process: a better explanation on the purpose of a multi-contextual approach (Why), concrete application of the main design characteristics like hierarchical decomposition that were introduced in chapter 2 (How), assurance that using a CVD or CVD-like approach does not beforehand exclude use of other methods and tools (How), and examples from previous real-life projects (How). Only once such guidance requests have been made and addressed should the more operational questions (What) get attention. Earlier than that simply discourages the attitude that needs to be fostered. The case studies, and results as described in (Kersten et al., 2018b) and (Kersten et al., 2018c) seem to confirm the expectation that if both experts (D'Souza and Renner, 2014) as well as minors (Davis, 2013) generally perform more creatively with no or little instruction, it should also be possible to encourage this in design engineering students.

The results also (indirectly) confirms those of (Cropley and Cropley, 2005) who tested the effects of presenting creativity to a class of engineering students, and then gave them an assignment where novelty would be one of the criteria, under the condition that their design also worked, i.e. was effective. Compared to a (small) 'control group' these students did display more creativity in the sense of novelty combined with effectiveness in their designs. For this class of 'regular' engineers it was just an experiment, with uncertain effects on their structural level of creativity. Design engineering students are supposed to have a higher intrinsic interest in and level of creativity, although not by default as high as design educators might hope and expect (Oraklibel et al., 2018). How that interest really affects the preference for light touch inspiration (Why, How to start) rather than a heavy touch instruction (What to do) might require more specific systematic research.

One might also debate whether the goal of educators should or should not be to make sure that all design students achieve a minimum standard of dealing with complexity. It may be doubted whether this "Leave no designer behind"-policy is really the intention of academic education. It may be acceptable that not all MSc-level design engineers climb the strategic mountain, and some become straightforward traditional design-experts. The increased importance of 21st-century skills (Saavedra and Opfer, 2012), does seem to suggest that in general the balance in most-desired skills is shifting from analytical thinking resulting in one best solution (Loye and Eisler, 1987) to one that signifies a pluralistic mindset. This might require teaching students to be adaptive (but not reactive) based on continuous reflection (Gonçalves et al., 2014), with due attention for reducing the risk of built-in bias if you do not look broadly enough (Gonçalves et al., 2016).

As the cases in this thesis, and its subsequent interpretation and reflection in this chapter, provide support for, a careful conclusion may be that design engineers who are not able to deal with Wilden's principle of requisite diversity (Wilden and Hammer, 1987) will not fare well in a design world where complexity is acknowledged and embraced. In CVD-terms, intentionally creating "shared insights" by synthesising intelligence from intentionally contextually diverse sources, and accepting that a large part of this process is highly uncertain, may not be something all design engineers want to and can do. But all of them can aspire to work with intent or purpose and build relationships with fellow designers to develop mutual trust (van der Bijl-Brouwer, 2018). Even more importantly, one aspect that this research scratched the surface of but was outside the main scope, is the growing necessity for design engineers to work together with professionals of other disciplines, in particular if their aim is to achieve impact on a large scale.

How does a result along these lines relate to the teaching of design thinking? While "design thinking" as such may or may not be explicitly taught in design curricula, it seems clear that design engineers when they have completed their education, have learned about this term. Therefore it is interesting to now briefly reflect on how the results of the cases compare with the conclusions about the desirable direction for the further evolution of design thinking in the meta-study as described in section 3.1.4.3 (Camacho, 2018).

- **Comprehensiveness: assume a wider vision, consider unexpected relations:** this seems fine enough as general guidance, but what further direction is given? CVD explicitly mentioning of contexts and systematic variation, as well as the shared design space where unexpected relations are likely to materialise, as the case studies demonstrated. This may in fact also increase the chance to better foresee unexpected consequences, e.g. for other than the initial target group
- **Simultaneity: understanding of the problem while developing the solution**: obviously designers recognise this as co-evolution (Dorst and Cross, 2001) and it aligns well with the design characteristic of discursiveness. The mention of a "solution" implies a (hidden) desire to arrive at something concrete, fixed, tangible and provides little guidance how to go about in better understanding the problem. At the same time, thinking in terms of "solutions" does not convey an appreciation of the inherent unsolvability of complex problems (Rittel and Webber, 1973).

- **Iteration: perform design cycle activities repeatedly:** there is hardly a designer to be found who would nowadays use a linear process with tightly controlled stage-gates (Cooper, 2008, Cooper, 2014). This is however not the same as discursive thinking, which is even more relevant for complex design tasks.
- **Graduality: gradual increase of understanding as input to gradually improve the solution:** this seems to strongly correspond with the muddling through strategy, emphasising small steps, including creating a path dependency (Jones, 2015) towards that one solution.
- **Divergence/ convergence: alternate between intuitive divergent and analytical convergent thinking:** somehow designers are fond of this way of visualising the process. There is little inherently wrong with that.

All in all, the CVD-approach does seem to capture virtually all of the suggested principles, while leaving more room – for better or worse – for the designers to make their own detailed decisions. This lack of room within design thinking may be one of the reasons why it is so popular: it creates the impression that by following the method, and early focus on a specific target group. the answer will easily follow. While the points above do convey a shift for “design thinkers” to enrich the basic principles, the underlying mindset is still one of a problem with ultimately a best solution. It may be doubted whether this is sufficient to face actual complex challenges that represent a pluralistic reality (Loye and Eisler, 1987).

How does CVD-like thinking deal with that pluralism? For one the explicit identification of multiple contexts provides a pluralistic basis. Looking beyond often geographically dominated context boundaries can be seen as intentional widening of perspectives, and because the variables then represent multiple dimensions of the problem, they highlight the interdependencies between the contexts that enable one to construct a well-informed path to the future, with options to vary when necessary.

In answer to the question on how to decide how many different contexts, i.e., perspectives, to include, the general advice is to rely on our knowledge of diminishing returns (Shephard and Färe, 1974): when more units are added, the *marginal* value of a unit starts to decrease at some point. Designers may not be able to or not even want to calculate that point, but based on experiences thus far it may be assumed that a maximum of three perspectives (multi-contextual use cases) should provide the dynamics in the design space that are intended for. Taking decisions on number and types of initial contexts, as well as determining the core variables to distinguish contexts can be guided by simple principles (Eisenhardt and Piezunka, 2011) and demonstrated with one or two examples, after which design engineers should be able to try it out themselves. This could be considered as an example of “freedom within a framework” (Gulati, 2018).

Final thought

The final chapter will dive deeper into the question not so much what is true in a binary sense but whether the approach that was introduced in this thesis – called Context Variation by Design – is worthy of being included in the Design Engineering Pantheon. As a bridge towards this examination in the final chapter 6, both from the point of view of practical usability as well as academic added value, a more in depth reflection on the conceptualisation of the CVD-approach is required first.

5.3 Verification of CVD Conceptualisation 1.0

In the previous sections we saw how the findings of the real-life case studies compared to the theory-based expectations that were framed in propositions. The structure of these propositions followed the main angles that were presented in section 2.1.3 as also became apparent in the discussion in section 5.2. Together these angles represented the overall framework to investigate the added value of the overall design-approach called Context Variation by Design, CVD 1.0. For that initial version, the *conceptualisation* was shown in figure 3.1 in section 3.1.6 and the Abstract shown in Appendix A2.1.

How does the discussion of and reflection on the empirical results in section 5.2, further scrutinised through interactions with the research stakeholders, feed into an upgrade of the conceptualisation of the design approach that took centre stage (CVD). This is addressed in this section 5.3.

The reflection of the implications of the empirical results is first visually represented below in figure 5.2. The figure includes numbered points of attention. These points are then described in more detail below the figure. In section 5.4 these attention points are then translated into *concrete suggestions for modification, i.e. improvement* towards a revised conceptualisation, CVD 2.0, which will be presented in chapter 6 as part of the answer to the Main Research Question.

As can be seen in the explanation of the points of attention below figure 5.2, these refer more to the *communication and presentation* of CVD rather than the fundamentals, i.e. the base principles of CVD. Most points are practical in nature, although there is likely (implicit) entanglement with the theoretical foundations. This is a sign that – in line with the principles of dealing with complexity – that entanglement should be respected, i.e., practical modifications have an academic relevance Finally, any point of attention can be relevant for multiple locations in the visual and as such can occur more than once. This is one more sign concerning the discursive nature of a design process.

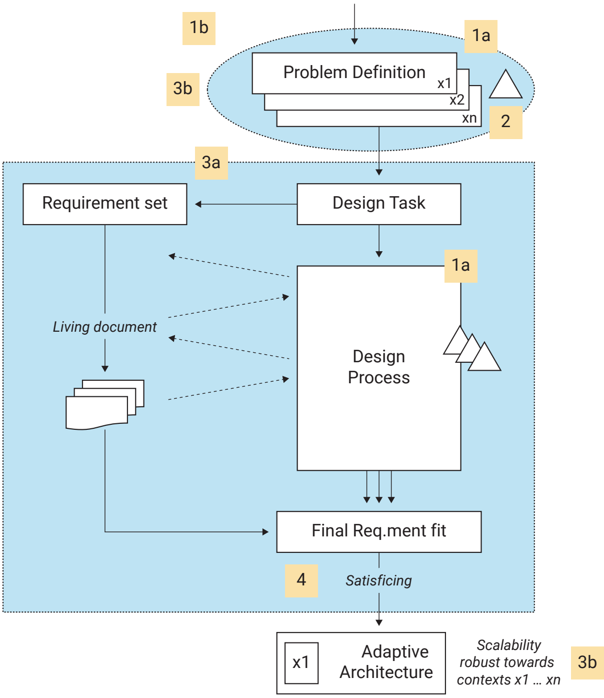


Figure 5.2 Points of attention related to CVD 1.0 – Figure 3.1 revisited

A detailed description of each of the indicated points of attention for potential improvements. Note that these improvements themselves are then addressed in section 5.4

1. **Providing guidance when suggesting variation before the design task.** In (R1.0) a designer came into action when it was clear what needed to be done , i.e. when the design task was set. It was therefore relatively clear and certain what type of result would come out of the design process. The specific features of the designed solution would by definition to some extent be unpredictable, given the systematic variation within the design task. With CVD 1.0 it was suggested that for large-scale problems occurring in a diversity of contexts, it is desirable to also apply this variation before the design task is set. This suggestion is by now largely supported by the case studies with two caveats:
   a) Design engineers experience practical questions referring to the problem definition stage (e.g., which and how many contexts to include) and the actual design process (e.g. when has enough information been obtained). They may be willing to acknowledge real-life complexity before they set to work, but as the cases show would still appreciate some guidance on addressing these matters.

b) Expectation management is required towards stakeholders who are focused on control (of process and outcome), like managers and some supervisors, that this way of working increases uncertainty and unpredictability requires adequate communication framed in such a way that it resonates with them.

2. **Contextual distinction goes beyond geography.** CVD enhances the use of the characteristic of systematic contextual variation by also applying it before the design task. The cases and discussion thereof suggest that to really capture benefits in full, this variation could be more varied than using just geographical distinctions and that this may need to be made clear *as much as possible beforehand*. Because CVD is extra relevant for issues that cross geographical boundaries, the choices for distinctions between contexts seemed to have gravitated towards choosing geographical ones, in most of the cases.
3. **Adequately managing expectations and formulating benefits.** The considerations for managers that are referred to in point 1b are primarily the following:
   a) The variation in the stage to arrive at a multiform problem definition and a design task that is robust towards a range of scenarios should be described in management terms as well. This is necessary to allow managers to consider that overall resources are likely lower than when variation towards different scenarios is done only after the initial design outcome (X1) is known.
   b) In terms of management uncertainty it therefore seems desirable to make an explicit distinction between short and long term. Both the unpredictability and the uncertainty regarding the consequences of the initial (short term, X1) design outcome may be higher when CVD is used because the design space is richer, but once it is there in the form of the adaptive architecture the uncertainty about the *scalability potential* towards the different scenarios (X1… Xn) is lower. Roughly speaking the more variation is done early on, the lower this second type of uncertainty. In a regular approach this is the reverse: less unpredictability, and therefore lower management uncertainty on the short term but more about the long term, i.e. the scalability *potential*. The eventual long term success of course depends on many other factors as well, including capability to operate on scale.
4. **The cost of high-quality information increases with time.** If the previous point would be formulated slightly differently, the more variation has been applied early on, the more creative the design process itself and the more information is available once important, costlier decisions need to be made. Managers benefit from higher quality information so if it takes a little more resources to improve that decision information, it is worth it: costs to achieve that quality

level of information after the initial design outcome has been developed would be much higher so the 'control' on costs for the longer term is improved.

The overarching pattern from these points of attention is the direct relation between benefits towards the 'end' and decisions at the start: substantial benefits can be achieved in later stages (adaptive design outcome, more clarity on scaling potential), and negative scenarios (lock-in, no insight in scalability potential) avoided, but only if considerations (importance of scaling across different contexts, relevance of multiple perspectives) were taken into account early on. The points of attention, based on the cases, show how much emphasis this overarching pattern deserves. This provides food for thought for an improved way to conceptualise and communicate the CVD-approach 2.0. What represents the right mix between a level of practical guidance for design engineers that still encourages their creativity and a level of information that allows managers to take decisions that are in line with a responsible resource allocation per stage?

5.4 Evolved thinking: towards CVD 2.0

In this section the last intermediate steps are taken so well-informed conclusions can be drawn in the final chapter and an upgraded conceptualisation of CVD can be presented. The main attention is required for section 5.4.1 where the identified points of *attention* with regards to the conceptualisation (figure 5.3) are turned into concrete points of *improvement* of CVD 1.0 towards version 2.0. In 5.4.2 a type of by-catch is presented in terms of early experiences to communicate the notion of one of the key constructs, the adaptive architecture to -mostly- non-designers.

5.4.1 Improvement points towards a conceptualisation CVD 2.0

Knowing what we have learned, what should be the changes in the conceptualisation, and in particular its framing towards design engineers, and managers, so it represents a real upgrade based on experiences in the cases? It is typically this confrontation with empirical reality that is the most relevant source for such an upgrade of the theory (conceptualisation).

As a final step before the upgrade, CVD 2.0, can be suggested in chapter 6, in this section the points of attention are translated into concrete improvement points. One purpose of the upgrade is to provide guidance to design engineers and managers that allows them to align their interests. The main improvements are first mentioned below, and then captured in figure 5.3. Not to confuse them with the numbered *points of attention* in figure 5.2 in the previous section, the numbers of the *improvement points* are formatted differently, i.e. I, II, III and so on.

To enhance recognisability, the points are structured according to the three main angles that were used in section 5.2 as well, which were the same as introduced in section 2.1.3

<u>Design Engineering arsenal</u>

Almost by necessity the points related to this angle are relevant for the education one as well.

I. **Dimensions**. Strengthen the variation of contexts by emphasising exploration of multiple key dimensions as distinction, not just geographical ones. Use dimensions that cross geographic boundaries to increase the robustness towards multiple scenario's.

II. **Number of scenarios (i.e. contexts).** To determine how many different scenarios are enough, a rule of thumb is to use a 2x2 matrix, using as axes two *key dimensions* that result in the most *relevant distinction* in light of the challenge to be tackled, For example, for a medical device the relevant key dimensions might be *proficiency of the end-user* and *travel time between diagnosis and treatment facility* rather than country borders. More than four scenarios is unlikely to yield sufficient marginal benefits, i.e., the added value of each additional scenario is likely to be too low. If practical considerations make four scenarios impossible as scope of the design task, consider to remove one or at most two scenarios that are the least likely or practical. This yields two to three scenarios ('contexts') that the multiform design task can focus on,

<u>Empirical framing: Scale/ sustainability/ inclusiveness/ management</u>

III. **More clarity about scalability *potential***. Clarify that while the uncertainty about the outcome of the initial design cycle increases with more variation at the start, the clarity about the *potential* for scalability, from a design engineering perspective, is higher at that point. In a regular process this is roughly the reverse. Appreciating this difference requires openness to accept the relevance of more than just short-term considerations.

IV. **A rich design space enables high-quality decisions**. Emphasise that quality of information is key when making the most important decisions. Using variations at an early stage means that the design space is richer and decisions therefore better informed. Obtaining high-quality information once an actual product has been developed is costlier.

V. **Communicating the value to different audiences**. The value and quality of the information obtained through the variation should be captured when the design task commences in a form that is also easily understandable by non-designers, e.g., a P.I.D. (Project Initiation Document), to document and communicate that value.

<u>Design engineering education</u>

VI. **Use of CVD does not shut out other methods and tools**. It should be made clear explicitly that the use of CVD as approach does not exclude other design methods and tools that design engineers have at their disposal; it might rather give some direction in picking which ones to use.

VII. **Shared insights represent the revergence point in the design process**. Designers like to think in terms of Divergence-Revergence-Convergence. When using CVD, one of these sequences is added before the design task. Within the design task the revergence points might be considered the place where insights are created. The "shared insights", as a result of the activities in the rich design space, are used for composing the design concepts.

VIII. **Design teams need diversity as well.** As is supported in much literature as well, the quality of the information and therefore decisions also depends on the diversity *within the team*. Ensure this diversity in an early enough stage. Note that this point is relevant for the management-angle as well. It could even be extended to other areas of expertise that are important for actual scaling, as suggested in chapter 2 (but beyond the scope of this thesis).

Figure 5.3 represents the visual conceptualisation of the improvement points I to VIII that together will feed into an upgrade of the conceptualisation, CVD 2.0 in the final chapter, both in visual and textual form. Again as in figure 5.2, a numbered point (I, II, etc) can occur more than once, amongst others referring to the discursive nature of a design process.

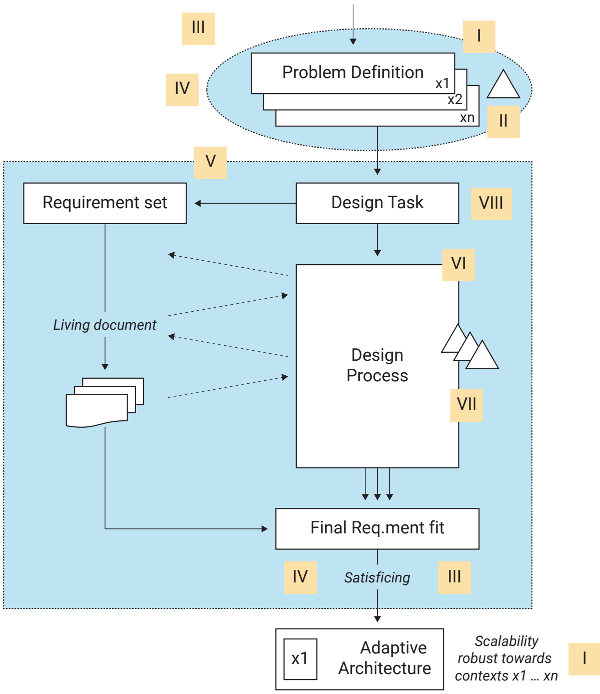


Figure 5.3 Points of improvement related to CVD 1.0

5.4.2 Communicating an adaptive architecture

Besides the detailed suggestions to eventually arrive at an upgraded conceptualisation of CVD that were based on the cases and their reflection, additional insights were obtained in conversations with mostly non-design engineer professionals, unrelated to the cases in this thesis. This is why these insights are presented here separately, as 'by-catch' as it were. These insights have not been subject to extensive systematic research yet, as this development occurred too late in the research for that to be organised. Nevertheless, these additional insights do seem to be sufficiently interesting to mention here.

As mentioned at point III in section 5.4.1, in the perception of decision makers the use of CVD might create more unpredictability about the design outcome and therefore creates undesirable management uncertainty but the actual reality is more nuanced: the *short term* design outcome might be more unpredictable than one in a regular (mono-context) design process, once that design outcome has been created, the *longer term potential for scalability* is clearer than with a mono-context approach.

To enhance understanding of this effect even further, in the period after the execution of the cases, conversations with various non-case related practitioners occurred. Based on these conversations it started to dawn how the notion of an "adaptive architecture" as outcome of the design process might be communicated effectively in particular to non-designers. This is to say, in a way that they recognise it based on their own experiences and thereby be less wary of the aforementioned assumed high level of unpredictability and uncertainty.

The notion that dawned, emerging from these conversations with professionals most of whom are not design engineers, was to present an adaptive architecture as a three-layer model. This turned out to resonate well in terms of recognisability with situations they have experienced in practice. Note that all mentions of "components" below are not limited to physical product features, but can also refer to services and any business model aspect.

1. *No lose/ No regret*: some elements of an architecture may be either 'fixed' for any conceivable scenario or don't involve (much) risk of being included. These are sometimes called "no lose" or "no regret" measures, or in this case components. The existence of this layer should provide some comfort, and implies there will be a fixed basis to use independent of the scenario.
2. *Adaptive/ modular*: on top of the fixed 'layer' a range of options can be devised, in an informed way. For each implementation cycle/ scenario the combination, variation and presence of exact components may be different, but at least the components are known.
3. *Scenario/ context-specific*: a layer with features that might be specific for one scenario or context. This may be the type of uncertainty that scares managers most, but at least now it can be clarified that it is only a (small) part of the total picture.

A way to visualise this three-layer adaptive architecture is shown in figure 5.4 below: the bottom part represents the element(s) of the architecture that are the same across contexts or that can be made the same without much risk ("no regret"), then a layer with an *informed* menu of components that consists of different but known variations, options to include or not or different combinations, resulting in a final composition per context that fits best with the requirements of that context. The final layer is the one which represents context-specific elements, which might include for example a linguistically appealing brand name, culture-favourable colours etc.

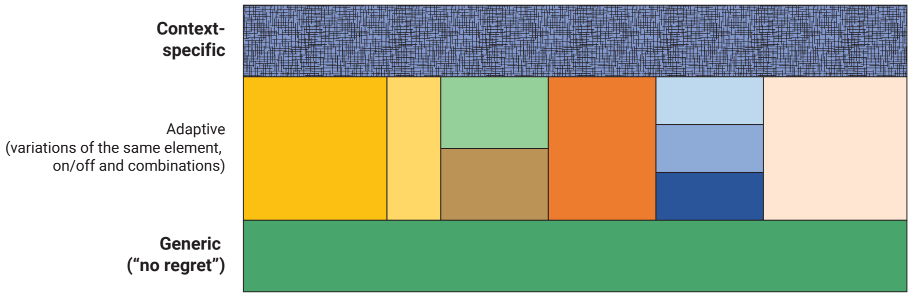


Figure 5.4 Adaptive architecture as three-layer model

Interestingly enough these "layers' can be applied to the implementation strategy as well, i.e. making that strategy adaptive. Some steps, e.g. choosing a globally recognisable brand name, are "no regret" (it can facilitate scaling and does not block first steps), some require a level of adaptiveness (mix and match) and the 'last mile' may require context-specific decisions. All are the result of a conscious process. The longer-term outlook, i.e., thinking consciously about multiple scenarios or contexts, creates a level of informed flexibility and reduces the risk of undesirable path-dependency.

This statement is visualised below in figure 5.5, and is the result of conversations with practitioners. Again, it is more a by-catch that could be used in next steps to investigate more in depth than a direct result from the empirical case-based research. The right part represents an adaptive strategy (with more scaling potential albeit without exact certainty which level of scale will be achieved by when), whereas the left part represents a path-dependent strategy with the reverse profile: more predictability and certainty but only for the potential with a narrow scope, e.g. one context.

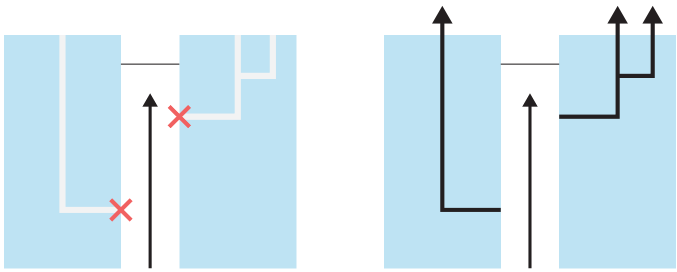


Figure 5.5 Reducing path dependency = increasing scaling potential

Chapter 6

Chapter 6: Conclusions and way forward

This chapter ties the preceding ones together by summarising the results so far in a number of ways. As the first step a summary is provided of the main results in terms of how the empirical insights compared with the propositions (6.1.1) and final reflection regarding the key constructs (6.1.2). This provides a step towards answering the Main Research Question as seen through the main angles that have provided structure throughout this thesis: *design engineering arsenal*, matters pertaining to *large scale problems and management considerations* and *design engineering education* (6.2.1 – 6.2.3) culminating in the main contributions to academic literature which are summarised in section 6.2.4. A reflection on the use of research methods is provided including discussion of limitations of this thesis (6.3). This reflection of the recent past is then translated towards the near future by providing a concise list of suggested research areas for next steps (6.4).

6.1 Summary of the findings from the cases

6.1.1 Propositions: patterns and plausibility

Based on the reflection in chapter 5, what are the implications of that reflection and discussion with regards to the level of plausibility of the propositions? Or do the results rather point at the necessity to reframe some of them, remove some and/or add others, in order to create more fruitful pathways towards future research, and practice? Be reminded that although numbers are mentioned, the statements below are not driven by desire for statistical or even numerical evidence. They merely point at general rough patterns regarding the *loose extent* to which empirical insights from the cases supported or opposed a proposition or mainly revealed the need for refinement of the proposition topic. These general patterns are one ingredient for the in-depth reflection and conclusions.

Empirical insights dominantly support propositions

The propositions that seem to receive the strongest support based on the empirical insights are 1, 4 and 5: a design approach that is built on early systematic variation *yields (more) unexpected insights*, *creates an architecture mindset* and *potentially has a high(er) quality* provided that performance and quality are considered through the lens of a multiform reality.

Need for refinement of proposition area dominates

For propositions 3, 7, 8, 9 (*shared understanding of richness*, *how management deals with complexity* and *how to introduce novelty to design engineers*) the cases do not fully support the proposition but certainly do not evidently oppose it either. Rather, the empirical insights suggest that other aspects for the associated themes in these propositions might be more relevant, or the theme might need to be captured differently. In other words: the insights with regards to these themes suggest the relevance of reframing the proposition topics.

For propositions 2 and 6 (*well-informed choices* and *inclusiveness*) the verdict seems to be balanced: a level of support can be observed complemented by some indication of opposition and results that encourage evolution of the framing of the topics that are covered in these propositions.

More specific cases/ research needed

In principle in the previous category but with an extra dimension: for proposition 10 (*management metrics that facilitate a multi-contextual approach*) the cases mostly came too early. Or formulated more accurately: the advanced topic of management metrics was not the core angle of the cases and insights in that matter are more circumstantial and indirect. This would therefore be an obvious area for further research.

6.1.2 Final reflection regarding the key constructs

Before moving towards presenting the answers to the Main Research Question, below a short final reflection now also based on the empirical part of the thesis, is provided with regards to the key defined constructs that were presented in section 3.6.1. This can be considered as a shared basis to feed into the broader conclusions in the next sections:

- **Contexts** can be distinguished in many different ways that are relevant for the design task. In one case that distinction might be a geographical delineation, in another it can be target groups, in yet another case physical circumstances. There is not one way in which contexts can meaningfully be distinguished and it turns out that this matters when analysing and interpreting a problem and deriving a design task. It seems to be desirable to emphasise this explicitly and with more examples to design engineers, to prevent that they suffice with going for the easy or obvious ones that capture the diversity of the problem only to a limited extent. In the domain of large scale sustainability-issues the obvious distinction is following geographical boundaries, but reality is more diverse than that.

- **Richness** in a design space is determined by the volume of information ('resolution') that is inherently relevant ('focus'). As is common knowledge by now, creativity to a large extent feeds on (different forms of) interaction. Because CVD encourages *volume* as well as *relevance* of information in the design space it thereby maximises the potential within the morphology stage to arrive at superior design results that inherently reflect interconnections between these design related contexts.
- To resonate with a broader audience, it seems to be useful to picture an **adaptive architecture as having three 'layers'** (generic, adaptive menu and context-specific), perhaps even enhanced by calling the first one "no regret" (i.e. applicable in any scenario) and modelling an implementation strategy in the same way. This division clarifies that there is more structure and less infinite variation than might be feared and therefore might be an effective way to manage expectations, e.g. to managers. Note that this result is one that is more inspired by conversations related to this thesis than it was found in the empirical cases. Still because its potential relevance for next steps it is included here.

Two final reflections that do not directly refer to these key defined constructs but seem important enough to mention nevertheless:

- **'Superiority' can – by definition – not be proven by exploratory research.** Signs for the high-quality nature of the design outcomes of a CVD-driven process have materialised in several case studies, in terms of perceived quality by principals, peers or as determined by comparative performance testing. It is more than one bridge too far to consider these outcomes as conclusive evidence of superiority pf the design approach that was used to achieve these outcomes. It was also not the primary goal of this inductively oriented thesis. It would require systematic, and arguably more purposefully created rather than real-life set-ups to collect the material that could possibly result in such conclusions. Such crafted instead of real-life based research could at the same time diminish the relevance of its outcomes in practice.
- **Diversity makes sense, also within design teams.** CVD provides a systemic perspective. The quality of this by definition diverse perspective is likely to be higher if it is the result of a strong cooperation between professionals with different skills also within the design team. Obviously the relevance of multi-skilled teams is far from a new notion. The results in the thesis do confirm this notion. The necessity to include people with other (professional) areas of expertise has been mentioned several times and is an interesting extension-area.

All in all, the statement can by now be made that a design engineering approach in which the points above would be incorporated can be expected to help address large scale sustainability problems in a superior way on a fundamental level.

6.2 Answering the Main Research Question (MRQ)

At this point in time all the ingredients have been gathered to provide an answer to the MRQ that was formulated in chapter 2:

Which theoretically and empirically supported insights and knowledge can be generated with regards to a design engineering approach that uses systematic variation of contexts before the design task has been set, in order to address, in particular, multi-contextual complex issues in society?

For ease of reading and writing, "*a design engineering approach that uses systematic (contextual) variation before the design task has been defined to incorporate the multi-contextual complexity of large-scale issues in society*" is represented by the approach that is the centre-piece of this thesis, Context Variation by Design, in short CVD.

Based on the preceding chapters, what are the results of using CVD and therefore its consequences for design engineers, managers and design engineering students according to the main angles as outlined in section 2.1.3? Both the active use of CVD 1.0 as well as the upgrade to CVD 2.0 is used in the answers below. The contributions to academic literature are implicitly mentioned throughout this chapter, the summary of the main contributions will be made specific in section 6.2.4.

As input for the following sub-sections a reminder is shown in the table below of the main characteristics of the regular approach (Regular 1.0), CVD 1.0. and improvements points for CVD 1.0 respectively as these have been unveiled throughout this thesis and captured respectively in figures 2.2, 3.1 and 5.3. This serves as run-up to presenting CVD 2.0, in section 6.2.1.

Approach	Section	Brief highlights
Regular, R1.0	2.2.1 Fig 2.2	Problem, and thereby the design task is fixed, variation occurs within the design process at several stages. The requirements evolve as a living document and interact with the design process resulting in a final fit for a satisficed solution. Eventual outcome is the optimal one for the chosen context (X) Robustness of solution towards new contexts after this first implementation (X) is unclear and creates a high level of management uncertainty regarding the scalability potential/ viability/ impact
CVD 1.0	3.1.6 Fig 3.1	Problem definition is unfixed from its initial context, it is multiform and robust towards several contexts Findings from different contexts are jointly addressed in a shared design space. The adaptive architecture satisfices requirements from multiple contexts (X1…Xn) Management unpredictability regarding scalability drops below the one for a regular approach after 1st implementation cycle (X1)
CVD 1.0 Improvements	5.4 Fig 5.3	Apply broad variation before the design task is set, i.e. not just by geographical boundaries Acknowledging connections between different parts of reality does not limit the choice of design methods and tools, it gives direction for their use. Addressing multiform design problems benefits from using teams with different skills, including within the design engineering domain. Some extent of unpredictability on scalability potential remains until the 1st implementation (X1) after which it quickly diminishes. This implies that high quality information for costly decisions is available sooner, and therefore against lower costs, than if the variation is postponed.

Table 6.1: Main characteristics of different approaches

The Main Research Question is now answered according to the main angles: *Design engineering arsenal*, *Large scale issues, (sustainable) impact and interaction between design and management* and *Design engineering education* in the next three sub-sections.

6.2.1 Design engineering arsenal

The history of systematic design (engineering) methods has been extensively discussed and this demonstrated that there are many ways how different aspects evolved during the centuries. However by and large the systematic part always resided in stages after the design task has been set. The CVD-approach suggested to use systematic variation before that point.

As all cases and resulting insights have shown, the dynamics in the design process are on the one hand influenced in seemingly positive ways, on the other it does require some adjustments for the design engineers. Interestingly, one of the points that has become apparent is that on the one hand "systematic" might be interpreted as something highly analytical with a set outcome, e.g., how many contexts to include. In reality, this variation, as well as decomposition in aspect-systems and choosing which ones are then the most relevant one to continue with, is in part also quite an intuitive, and even pragmatic, process.

This seeming tension is exactly what the cases have highlighted. Design engineers who can deal with such tensions seem to stand a much better chance of dealing with all other challenges that a complex design assignment throws their way. In that sense, being able to make sense of the process before the design task is properly clarified could be considered as an aptitude-test for design engineers to grasp what is to follow. More thoughts about this follow in section 6.2.3 when the consequences for design education are addressed.

One of the implicit but looming questions is the -demonstrated- added value compared to the existing design engineer's methodical pantheon. The cases have shown in terms of experiences and results that the CVD-approach can certainly help design engineers, provided they have some talent for dealing with -short term- uncertainty. More explicit mentioning of the *complementarity* of CVD and its potential to "put things into context" is likely to help acceptance and adoption of the approach. This to explicitly prevent the thought that it *excludes* other tools and methods, in particular ones that are related to systemic design. Amongst others the conceptual contributions to the notion of richness in a conceptual design space seems to be complementary as well as that it strengthens other methods.

The specific (added) value compared with design thinking, in methodical terms, is equally challenging to express in such a way that its protagonists will accept it as addition to the academic discourse. Much value is in the eye of the beholder. What can be said with a sufficient level of objectivity is that the *explicit* range of used perspectives to address any problem with CVD is broader than with design thinking. Interestingly, some might consider this aspect to be the downside of CVD-type thinking because it might dilute focus. It is exactly the role that this focus should play, and the timing of creating it, that determines the direction of the debate. If (concrete) end-user focus to create a specific solution is the goal, then “Design thinking” seems a sensible means. If diversity of perspectives to get informed on the full nature of the problem before deciding where to focus in the first place is the goal, then CVD-like thinking probably leads to better results. It is not difficult to see that both situations can occur and therefore both types of thinking have their own application areas.

To capture the above, figure 6.1 below represents the visual version of the conceptualisation of CVD 2.0, in the same style as the ones for the Regular approach (figure 2.2) and CVD 1,0 (figure 3.1). This version captures all changes as discussed in section 5.4 and figure 5.3. Because the visualisation has evolved iteratively since the first one, the changes might seem very small. When however comparing it with the visual of the regular process (figure 2,2), and considering the intention behind the changes as explored in this thesis, it should be clear that the changes do represent more than a small ‘tweak’. Once the mindset of the design engineer has been geared towards acknowledging a multi-contextual reality, the approach was however demonstrated to be feasible. In other words, the change represents “a new perspective while not being totally alien to design engineers”.

A full textual version of CVD 2.0 is included in Appendix A6.1 in the form of an Abstract. This makes it comparable to the Abstract for CVD 1.0 (Appendix A2.1) as it was conveyed around the start of this thesis. The main differences in Appendix A6.1 with how CVD 1.0 was conveyed are marked with an * and the key notions are underlined. Most of these key notions have not changed since CVD 1.0, signifying that the “upgrade” is more about the communication of specific elements than modification of the fundamentals.

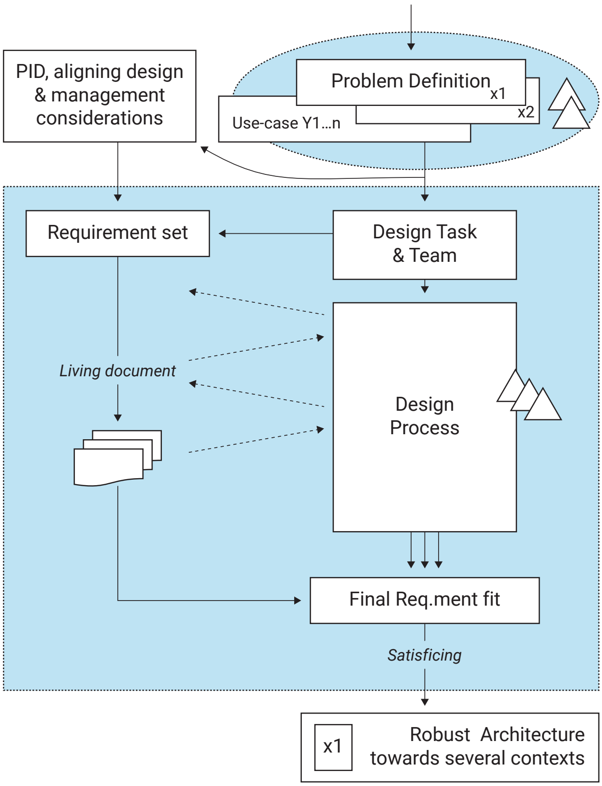


Figure 6.1 Visual conceptualisation of CVD 2.0

Further discussion and socialisation of this visual may in the (near) future result in a version that might resonate more with non-design engineering audiences.

6.2.2 Empirical framing: large-scale issues, associated impact and management considerations

In principle, a mindset and design approach that acknowledges and respects complexity basically means that considering possible connections between end-points (e.g., end-users) are seen as more relevant to understand any given large scale problem than understanding just these end-points themselves. If one does not accept this underlying premise then it will be difficult to see the results as presented in a positive light.

What the thesis has shown however is that this premise seems to lead to a workable alternative for early focus by means of varying contexts, and context-boundary crossing use-cases early on instead of picking one specific context and use-case to start on in isolation. This former approach, as argued, seems particularly relevant for the aforementioned large-scale sustainability-related issues. The obvious attention point is then the possible broadness of the scope of the design task and the practical challenges in making sense of the diverse and voluminous intelligence that this broad(er) scope contains. The scope of the design task cannot cover all factors and challenges that eventually determine success on a larger scale. Sourcing insights from multiple contexts is nevertheless likely to reveal some elements of these challenges so implementers can at least become aware of them.

Another observation is the on the one hand inherent link of the CVD-approach with notions of inclusiveness and social impact, as intended in the same line as the Sustainable Development Goals (SDGs). I.e., design interventions need to take into account the positions of "disenfranchised groups in society" and the better they manage to do that and address the problems of these groups, the more social impact is made. In efforts to promote the CVD-approach one would think that the horizon of a wider range of served beneficiaries and less end-to-end effort in doing so would be of strong interest to the development sector and its funders. Based on the current empirical findings obtained from the cases, it is not yet obvious what would be required to indeed trigger that interest. Possibly the outlook of positive impact for a more diverse group whose identities are more difficult to conceive at an early stage is currently still beaten by the outlook of having impact on a less diverse but more concrete group. The specific impact in the latter case might be easier to contemplate, and therefore to 'sell' and communicate, in particular in a world driven by short-term 'success' metrics.

If that situation is to be changed it seems that a role can be played by (re) framing several metrics, to ones that convey a holistic, systemic and/or longer term view on achieving social and societal impact. Some candidates were explored in cases and have been lightly discussed in this thesis: *end-to-end (= scaled) development and implementation costs*, *time-to-markets*, *assessing inclusiveness and impact by <u>diversity</u> of the total beneficiary-group not (just) the <u>number</u> of (initial) people*, *potential to trend towards zero marginal costs*, *quality defined as fitness-to-multiple-use*, *effects framed more in terms of avoided losses than potential gains*. The type of research and cases were not very suitable to get in-depth into this area but the very fact that such a range of suggestions emerged can be interpreted as yet another sign that if you change the perspective you get new ideas.

All of these considerations taken together do signify that the current period in time, driven by *Sustainability* as shown in figure 2.3, seems to have gained a useful ally with the CVD-approach. The issues of more uncertainty, less controllability and more attention for societal relevance have not been 'solved' but the CVD-approach explicitly considers these aspects. Thereby it may help design engineers to *work with* these elements of complex challenges in a constructive way.

There is one more angle for considering the aspect of management (and funder) uncertainty which has been referred to several times in chapter 5: the way how unpredictability and the related uncertainty with regards to scaling *potential* develops with time when using the different approaches. To close off this section this point is shown graphically in figure 6.2, which might support possible future research into this matter. It depicts the indicative pattern of the development of "management uncertainty regarding the potential to scale beyond the initial context" for the regular (R1.0, CVD 1.0 and CVD 2.0 approaches, with one curve for each.

The R1.0 curve provides the least short-term management uncertainty, i.e. starts out low on the y-axis, because the scope of the problem under consideration and therefore the design task is relatively limited and focused. After the design outcome is known, and first considerations for scaling emerge, the uncertainty about this scalability potential rise because there managers nor designers have no consciously sought information on this, The CVD graphs start our high on the y-axis because the diversity of perspectives and contexts makes the short-term outcome more uncertain for managers. The reason why the CVD 2.0-curve starts out above the one for CVD 1.0 is because the more explicit emphasis for broader variation of contexts, i.e., explicitly look beyond geographical boundaries, is likely to cause more initial uncertainty with managers. And exactly because of the initial broader consideration for which design engineers now feel more room, there is a good chance that the design outcome, the adaptive architecture is inherently adaptive to even more scenarios. That is the reason why the curve drops below the line for CVD 1.0 once the design outcome is in sight.

Note that this visual provides only a rough idea that can be explored further in particular with people in management positions, rather than that it implies any level of mathematical precision. Also, to be clear, the *actual* scalability in practice of course depends on many factors. The graph only captures the indicative curves about the *uncertainty of the scalability potential*, based on the arguments as provided above.

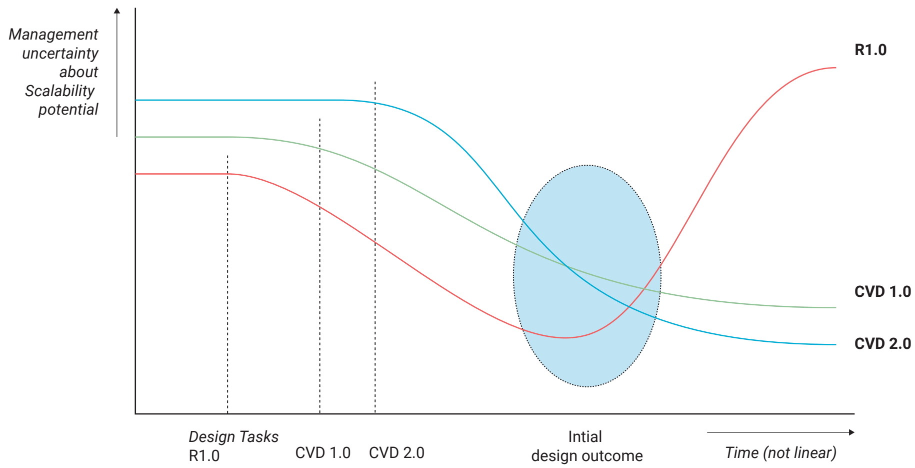


Figure 6.2: Development of management uncertainty on potential to scale

6.2.3 Empirical framing: design engineering education

As has been apparent from the start, the empirical framing angle of this thesis also included the specific implications for design engineering education. If the CVD-approach adds value to a design engineer's arsenal as section 6.2.1 implies, what are the associated conclusions with regards to the way how it, and novelty in general, might best be integrated in design engineering curricula?

Framing of novelty

One conclusion in that respect is that effective integration of novelty in design engineering curricula, with CVD as case in point, is the suggestion, as made by this researcher after numerous interactions with designers and other stakeholders of this research, that when getting students, and perhaps people in general, engaged into trying out something new it may be less about emphasising different 'facts' or principles than it is about *conveying* these differently. This, as mentioned before, is one way how the novelty that is introduced does adhere to the principle of "adjacent possible" (Johnson, 2011). Two (out of many possible) examples that illustrate this point:

- use of CVD does not exclude use of other design methods and tools, on the contrary. Yet, by emphasising a particular approach, in this case CVD, some students implicitly thought it was intended to replace much of what they had learned: they considered the suggestion of using CVD as being confronted with different 'facts' whereas it was more about suggesting an additional way of looking at things, i.e. how to approach a design challenge. The non-exclusiveness of CVD might need to be stated as explicitly as possible to (junior) design engineers to prevent such misunderstanding.

- the apparent difficulty for students to recognise, deal with and make concrete positive use of the design characteristic of *hierarchical decomposition in aspect systems* points at the desirability to reframe this. Hence the suggestions in chapter 5 to use framing of key variables that go beyond the more intuitively understandable contextual boundaries. This results in delineations that at least encourage students to consider variations not just in a geographical sense. By taking the next steps and thinking while using other types of demarcation, the inclusion of more diverse, but guaranteed to be relevant, perspectives is encouraged even more. To achieve this, one possible way to describe "aspect systems" might be "multi-contextual use cases". The main goal of this reframing (=presenting something differently) would be to emphasise the notion of respecting connections between the contexts within the larger system more than just the end-points. If using a term that is more familiar to (student) designers as opposed to the more challenging notion of "aspect systems", to achieves that, this might be acceptable as a pragmatic proxy in the communication. Whether this particular reframing is effective in practice in terms of encouraging design students to consider a wide(r) range of contextual variations is a matter for further investigation.

Communication of purpose and benefits

Another conclusion seems to be that the benefits also need to be conveyed in a clear(er) way. A few results seem extra relevant to recap here: the notion that the quality of design choices and in all likelihood the quality as well as the (un)intended adaptiveness of the end result is positively affected. In other words, both the informed generalisability – intended applicability of base architecture in diverse range of situations, known unknowns - as well as the latent functional creativity – unspecified relevance of the architecture for unforeseen circumstances, unknown unknowns (Snowden and Boone, 2007) – are likely to be (much) higher. All this is specifically caused by acknowledging the role of intent, i.e. by design, and thereby putting the designer centre stage instead of in the role of "the one who can visualise and materialise other people's ideas". With mastering CVD-like systemic approaches these design-specific skills now *strengthen* a strategic role, instead of replacing it. These are prospects that design engineers-to-be might be sensitive for, in a positive way. Although, as discussed, not all may have the aspirations and/or skills to do so.

Attitude influences Behaviour and/or vice versa?

An interesting implicit point has been raised about the question whether the existing base attitude that (junior) design engineers have determines their openness to using CVD-like approaches, or that the actual behaviour of starting to use such approaches influences the base-attitude. It's likely to be a mutual dependency. If you are not open to novelty and variety of perspectives, you not only are less likely to be willing to try out new approaches, but it also influences the interpretation of the relevance of that novelty. For example: CVD-framing revolves around sourcing and incorporating diverse perspectives to reveal (unexpected) connections to feed into design choices. If you are geared towards, i.e., have a base attitude of, cherishing clarity and optimisation as was suggested by (Oraklibel et al., 2018) design students might surprisingly do, such a starting point is bound to create a feeling of confusion, not daring to focus on the main end-user, not making choices etc. Whereas if you are geared towards being open to surprises, not being too attached to a specific product as result and not striving for *one* best solution, this starting point can easily be recognised as preventing heads down design (Myerson, 2015).

Novelty for all?

Finally the dilemma – which has been touched upon several times already – *Leave no student (design engineer) behind* ("*Everyone needs to be on board*") vs *If you don't understand it, don't use it* ("No one forces you to take on the challenge if you think it is not for you"). As for just about all other topics in this thesis the key point seems to be to circumvent the pitfall of a considering it to be a binary choice. In simple words: it is not a question of a simple A or B. In order to at the same time as an educator get a sense for the base attitude of the students, and for the students to get a sense of their ability to grasp the novelty that they are presented with, two interesting directions can be distinguished:

1. To ease junior design engineers, including students, into using or considering novel approaches, it might be worthwhile to not go for the Big Bang, but start with a smaller steps. In other words: it should be possible to explain any novelty and demonstrate its potential by means of small exercises that are representative for the impact on the design process. In the case of CVD, such exercises could be designed to test how students deal with aspects like choosing multiple perspectives from the very start (which and how), bringing these together (how), dealing with more conflicting demands (satisficing vs optimising), developing rapport with managers (time-to-MVP vs Time-to-markets; communicating the effect on scaling potential) etc. By having 'smelled' at the novelty in manageable chunks, it should become easier to decide for whom consuming the entire meal is a way to go. As mentioned, not all design engineers may want to, or are able to, think in such strategic fashions. That is alright. There are other worthwhile roles as well.

2. Apart from providing a good starting point, the rest of the (supervision) process might be helped with by means of putting more emphasis on (probing) questions than on early judgement. This goes both for supervisors as well as junior design engineers themselves. In early stages of a design process too little is known to label it is (ir)relevant, good/ bad etc. Instead, they should be – encouraged to – ask questions like “Why is this the core of the problem?”, “Are other interesting perspectives possible?”, “Is this the most relevant contextual distinction?”, “Have sufficient people been asked about their experience?”, “Who should be included in the rich design space?” and so forth. Probing questions that almost force the designer to think in terms of diversity, richness, connections. And when the time is ripe, supervision questions can then rather do the opposite to guide them to the revergence and convergence activities: “What do you expect the marginal value to be of talking to more people”, “What perspective are you missing, or is this about it?”, “Do you see promising patterns emerging from your results so far?”. In other words, without pushing any decision contents wise, on a process level the right questions at the right time can surely support less experienced design engineers. Of course, the supervisors in this position then also need to see the value of this themselves.

6.2.4 Main contributions to academic literature

To signify an important step in the acceptance of CVD in the arsenal of design engineers, it is worth mentioning that it is included in the most recent edition of the Delft Design Guide (Van Boeijen et al., 2020, rev. ed.).

Additionally, below a list is provided with what might be considered to be the main contributions that this thesis has provided to academic literature. This is one building block for the suggestions in section 6.4 on what might be useful next steps for academic researchers.

- **Enriching the concept of framing.** Early systematic variation before the design task is set, creates conditions for a rich(er) design space that allows for an adaptive architecture to be developed that not only covers a wider range of requirements but also does so in a way that invokes creative design decisions. The eventual performance of a specific implementation does not have to suffer from this, far from it (see e.g. case #3). This entire notion enriches the academic literature in terms of the value of (re)framing of a societal problem and the subsequent design task (Paton and Dorst, 2011, Dorst, 2015).
- **Key problem dimensions define contexts.** The explicit attention for contextual variation and looking beyond (geographical) boundaries for that variation might invoke more interest in how to approach and decompose problems and construct the design task. Acknowledging

the relevance of key dimensions that cross the more obvious contextual delineations, e.g. as marked by countries, seems a pragmatic proxy for decomposition in aspect systems that cross sub-system (e.g. country) borders. Thereby it is likely to enrich the use of (re)framing (Paton and Dorst, 2011, Dorst, 2015), systemic design (Jones, 2014) and systems oriented design (Sevaldson, 2017b) while fully acknowledging the value of these design approaches.

- **Systemic design tools combine intent with concrete steps.** Building on the identified risks of path-dependent design (Jones, 2015) and heads down design (Myerson, 2015), the CVD-approach reduces these risks. To let this be appreciated sufficiently by decision makers, a longer term intent and metrics to match (e.g. time to markets) needs to be combined with the aim to achieve an -informed- adaptive design outcome. This adaptivity does not imply that all future circumstances are foreseen, but because a more pluralistic mindset was used (Stirling, 2008) the odds that this design outcome can play into new circumstances are better. This combination seems to offer a richer way forward for large-scale, complex design challenges than is encouraged by focus on the explicit notion of “acting opportunistically by taking whatever action is possible at the moment” (Norman and Stappers, 2015). This is not meant to imply that this strategy is fully incompatible with having a longer term perspective as also stressed by (Ma, 2019), but it might need to be made more explicit in that case.
- **The rise of richness.** The effort to gain better understanding of the construct of richness in the conceptual design space represents a potentially important step in using it more explicitly to enhance discussions during the design process. On top of the general attention that this thesis paid to this construct, the trial with the three-part working definition (representing multiple perspectives, encouraging connections and be generative) built on individual work e.g., (Oades-Sese and Esquivel, 2011, Montuori, 2011, Sevaldson, 2008, Sevaldson, 2009, Bushe, 2013) and attempted to integrate that work. This attempt seems to merit follow-up.
- **Management metrics need to be Wise, more so than Smart.** Although not yet addressed in depth, the research suggests the relevance of investigating how longer term oriented metrics such as time to markets, costs across multiple implementation rounds, trending to zero marginal costs, inclusiveness measured by diversity of target groups, might be conducive to guide a strategy that puts large scale diversity centre-stage. Thereby it might take away too much focus on achieving SMART targets (Doran, 1981), and enriches the view on how to still be ‘in control’ (Mundy, 2010).
- **Bearable novelty.** Introducing novelty to design engineers during their education might work best by adhering to the adjacent possible principle (Johnson, 2011) as well as “freedom within a framework”

(Gulati, 2018). This can be done by finding a right balance between allowing them to 'make it their own' while recognising that a form of practical guidance is still sensible, especially on Why and How levels perhaps more so than What. In the case of more strategically oriented design approaches the extent to which they then are able to deal with a lack of detailed instructions can perhaps be seen as an indicator for the positions they might want to aspire to in their design careers. This builds on suggestions regarding the reality of the diversity of the portfolio of tasks (Baldassarre et al., 2019).

- **Overview and direction.** The experiences gained with suggesting systematic and systemic design in general and the CVD-approach in particular demonstrate that there is much potential for combining several tools like Gigamapping (Sevaldson, 2017a) and various forms of system maps. These tools encourage a systemic outlook and representing it in a visual way, CVD provides explicit direction in deciding on the scope of the system under consideration, also for a longer term.
- **The relevance and limitations of multi-contextual design engineering**. In particular referring to the six challenges to scaling early successes (Banerjee et al., 2017), this thesis has contributed to insights regarding two of these challenges, the *context dependence in pilots* and *site selection bias*. Both are mentioned as specific challenges in more common approaches, even ones that can afford to do controlled trials with large numbers. Because of intentional contextual variations that are based on using the key dimensions of the problem, not just easy access or obvious characteristics, the challenges as found can for the most part be prevented. This does not make the initial early stages easier, it can however contribute to speed up the scaling stages because several considerations and replication related research has already been taken care of. The other challenges, including political ones, spill overs and general implementation challenges are not immediately 'solved' by the suggested design engineering approach. Still, the chance is clearly there that a rich design space in which insights from different relevant contexts are combined yields information that points implementers in the direction of likely tensions, forces to take into account, dilemmas and so on, that will appear during the scaling phase. This is true both for the quantitative angle of scaling as for the more qualitative one, i.e. achieving societal impact. The relevance of a rich design engineering approach is not all-encompassing. It is not trivial either.
- **Multi-contextual design thinking.** The CVD approach enriches the basic elements of design thinking (user focus and empathy, practice based prototyping and testing) with the aim to do this for multiple user groups in parallel and with some longer term perspective built in. Thereby the risk is reduced that the well-intentioned user-

oriented focus (Norman, 1988, Brown, 2008) is considered too narrowly, implicitly excluding the needs of future but foreseeable user groups, their needs and to an extent more general broader societal consequences (Rittel and Webber, 1973).

6.3 Methodological Reflection: looking backward and looking forward

This section contains a reflection on the use of the methods that were used during the process to write and construct this thesis. Primarily to reflect how the methods made sense (or less so) for the different purposes of this research (6.3.1), discussing factors that might be perceived as limiting the validity or generalisability of the results (6.3.2) and the methodological lessons or at least suggestions for next steps (6.3.3).

6.3.1 Verification (CVD 1.0) and further development (CVD 2.0)

As a reminder, the main methodological components of this inductive research were: 1. literature research, culminating in conceptualisation of the research reality, 2. case research and 3. continuous use of the reflective practitioner approach. The case-based research and the interpretation of the results did not happen from a parametric perspective. This section reflects on a number of methodological topics.

Use of propositions

Given the very early stage of development of the theme under investigation, where it is still highly unclear which types of detailed questions might be relevant, using a primarily qualitative and inductive approach is defensible. The starting points of the empirical part were more a jump off platform than a fixed starting line. In first instance the starting points were the main components of the literature research that was initiated in chapter 2 and culminated in chapter 3. One could also say that the starting points of the empirical part, which has arguably brought most real-life added value, are the propositions at the end of chapter 3 (3.6.2). The exploratory stage of the research theme encouraged the use of well-informed a-priori *expectations*, in other words propositions. This still seems to be the right choice in between softer corollaries and stronger hypotheses.

Reproducibility of analysis of theory - propositions

It might be an interesting thought-exercise to wonder how reproducible the results of the literature study are, and especially the step from literature towards the propositions. One might argue that the propositions are not the result of strict analytical reasoning and are thus not fully reproducible if another researcher would have been in the lead. This, to be sure, is in all likelihood true, and is in fact desirable for explorative research.

The sourcing of potentially relevant academic and other writings was wide, and some elements turned out to be more usable than others. Based on identification of main angles in section 2.1.3, informed choices were made concerning the *themes* (section 3.1 – 3.5). The selection and variation within each theme was wide *and* non-arbitrary. Therefore the likelihood – to be interpreted in a non-mathematical way – was increased that the literature research would eventually result in propositions that were *unexpected as well as relevant* and in part would reflect interconnections between the different themes.

One consequence of the inductive reflective approach is that the result of the process steps (problem – conceptualisation – literature – propositions) eventually represent a convergence that strongly depends on the researcher in question. As explained several times, the main way to mitigate the risk of too much subjective bias was to continuously interact with a variety of stakeholders. For the theoretical pillar this refers to formulating the problem, interpreting existing literature, summarising the literature in its most valuable ingredients, combining these into propositions. In the end the final choices were made by the researcher, so the results represent one possible convergence. This is an inherent and unavoidable aspect of this type of research. How acceptable this particular convergence is, is to be assessed by the reader.

Reproducibility of empirical results – cases and insights

A similar question as for the results of the literature review might be asked of the interpretation of the cases, in particular creating the overarching insights: These insights again represent one possible convergence, this time of the empirical process (case selection – case description and interpretation – identifying case-specific findings – creating proposition-linked insights). The execution of the cases themselves were dependent on the specific designers who were involved. Would different designers have come to different results? The answer is that results on micro level would likely have been different which is what explorative research is about.

When assessing the plausibility of the relevance of the results it can be put forward that in all cases either the verification of the main results, or the actual sample size, was not singular. Put more simply: if the lead designer was one student, results have been verified in various ways by others and if the lead designer was a group or a class, the results already included a level of intersubjectivity. This, in this stage of exploring the theme, is as good as it gets.

Similarly, with the empirical results of the cases as a given, how reproducible are the final steps of the empirical part of this thesis, i.e., the formulation of case-based findings in relation to the propositions in section 4.2 and Appendix A4.3 and their translation into overarching proposition-linked insights in section 4.3? These two steps were, in a similar way as with the theory-based propositions, to a large extent dependent on the researcher, and made as intersubjective as possible by means of the oft-mentioned discussions and different forms of interactions with a variety of design experts. The steps to move from sources to results in both instances were fully transparent in the sense that no hidden information or data has been used, or existing information or data had been omitted.

The short answer to both questions is therefore that this process represents one possible, and by definition not the only, convergence. With another researcher and/or other design experts whom the researcher interacted with, details of results *might* have been different especially on detail-level. This is to be expected in a process where the reflective practitioner approach is used. The plausibility of the relevance of *this* particular convergence can be fully assessed based on all the available information regarding the cases (descriptions, references, publications, findings) and by taking note of the process as it was followed and described throughout this thesis.

As a general statement to close off this reflection on the reproducibility of the different types of results (propositions, cases and insights), be reminded that in the “web that weaves complexity” (Montuori, 2011), it makes little sense to look for the one certain, universally true answer.

6.3.2 Limitations of the thesis: looking backward

Before the next sub-section offers suggestions for methodological considerations for next steps, it is the right moment to have a brief look at the limitations in the approach for this thesis. Not so much limitations that harm the validity of the results, but more in the sense of: since we have progressed, what types of limitations that were encountered do we now have more understanding about and can we circumvent or take more informed decisions about in the future?

Type of lead designers

With very few exceptions, the lead designers in the cases were final-year MSc-students Industrial Design Engineering, meaning they are in at least their 5th year of training for this procession. While near the end of their academic career for now, they are at the very start of their professional career. What might have been the influence on the results of the cases of their status as professional novices as opposed to expert designers? How different would the results have been if the latter group would have agreed to participate as lead designers as opposed to supervisors in the student assignments? The answer is open for now. A few remarks are shared here, without one overarching conclusion. This theme is widely researched, but has not been actively explored in this thesis. The remarks below are therefore ‘educated statements’:

1. Expert designers probably by virtue of their experience might have a more diverse outlook on design challenges that resembles the CVD-mindset to some extent already. Therefore, differences between 'with and without CVD' might have been less pronounced. On the other hand, experts in any discipline are often quite convinced that their way is the right way. Given the fact that explicit attention for systemic design as opposed to user-centred design is not yet mainstream, it is just as likely that expert designers might not (all) have this broader, more diverse outlook as main design attitude.
2. While still in the education system, professionals-to-be, in this case design engineers, are more likely to be open to try new things when being nudged to consider this, as long as they can still pass courses. They are still in learning mode so don't mind to learn something even if it is challenging. Seasoned designers might, as became apparent at the start of this thesis-trajectory have pragmatic reasons to not use new methods until they have seen substantial evidence that the benefits for them are large enough.
3. All in all, for the exploratory research that was undertaken the choice for novice (i.e., final-year students), highly educated design engineers seems not only a defensible one but probably a better one than using expert designers, even leaving aside the practical but relevant difficulty in gaining an equal level of access to expert designers and their willingness and possibility to share (in part confidential) information.

Validity, reproducibility and transparency

In the discussion on the reproducibility of results in 6.3.1, the tentative conclusion was that on the one hand the results, both of the literature study as well as of the cases, would almost certainly not be the same with different researchers or designers in the lead. As mentioned, this is not just acceptable, but even desirable for this type of research. The only relevant question is what this means for assessing the validity of the results as presented in this thesis. This requires an assessment of the validity of the *research approach as a whole*, i.e. from problem area to MRQ to choice of research methods to literature scoping and so on, not just of the micro results.

Still, when talking about micro results, below a few statements are made, focused on the empirical results.

Almost all of the results in the cases are of a qualitative nature, in some instances (like evaluations in the broad cases) 'coded' in a numerical way. Qualitative results are by definition more subject to potentially different interpretation. This is, however, simply a fact of (academic) life. The stage of the research did not allow to work with testable hypotheses yet, and in fact the differences in interpretation, e.g., between experts for richness (case #1) and between students who worked in the same group on the process (case #4) show how arbitrary any upfront choices would have been for coding to – artificially – enable statistical analysis.

Therefore, three ways have been used to deal with this inherent subjectivity:

- Bringing subjective assessments (= opinions) together into one overall number and then discussing the results. For example all assessments in case #1.
- Do first small-scale trials to test how making interpretations intersubjective by introducing a shared (rich) definition might be more helpful than relying on subjective interpretations. For example the test with the three-part working definition using different assessors in case #2 and using the list of closed questions in case #5.
- To prevent a possible black-box feeling with the reader of this thesis in terms of questioning the origins of the 'results' of the theoretical part (Propositions) and the empirical part (Insights), both are fully traceable. Meaning, anyone who puts in the time can follow the two main empirical tracks structured as *Source – Summary*: Track 1. literature in chapter 3 - propositions in section 3.6, Track 2. case study-specific insights (section 4.2) – overarching insights per proposition (section 4.3). These two tracks formed the combined basis for overarching discussion and conclusions in chapters 5 and 6. As mentioned before, this process was not one of analytical reasoning, with one right answer. Other people might indeed have arrived at different results. The only relevant question is, are the results in *this* thesis defendable, based on the process with steps that were transparently conveyed?

All in all, this points at something to be aware of, without it being a limitation in terms of the general validity of the results: should (next) research rather go wide or deep?

Width vs depth

Whereas the selection of case studies and considerations for that selection show that there was due attention for thinking *deeply* about a specific case *and* paying *broad* attention to the experiences of designers, this has had a small cost: lack of time to systematically take one or two specific lines of research several steps further.

Some of the topics that initial promising results were achieved for almost 'screamed' for follow up, to quickly take next steps and/or verify first results. Two examples of this are 1. the line of research on 'measuring' richness and its added value in creating a shared understanding for complexity in the design space, and 2. in-depth research into the preferences of design engineers for the type of guidance. It is conceivable to set up a host of consecutive tests for such topics, although it would require a substantial pool of design students. If this would have happened, some of the research areas might now have been explored more in depth. A practical bottleneck in that sense was the limited (to no) access to large groups of suitable students, or to smaller consecutive groups of students who, in order not to prime them too early, could be kept in the dark about the CVD-approach and thinking behind it. Additionally, in particular related to the second example, as has been discussed in chapter 3, there is no blueprint to deal with complexity, so putting effort into discovering such a blueprint, e.g. regarding effective guidance, might not have been the best use of time in the first place.

Again referring to the explorative stage of the theme, for now the temptation to dig deeper in some areas perhaps striking gold in these specific spots, was fought. Instead the broadness of the theme, and keeping an open mind as to where future sources of intellectual and practical wealth might reside, remained the main driver. This is not a limitation in absolute sense, it rather explains why some partial research areas within the theme have not been explored further yet.

Managerial considerations

As discussed before, while some of the propositions (7, 9, 10) referred to management considerations, results to feed into the empirical insights that were relevant for these propositions were mostly indirect. Some discussions in hindsight give interesting ingredients for these insights. For example, like table 5.1 illustrates, the results point more towards the necessity of reframing the management-related propositions. For almost all of the cases the representatives of the principals who might be considered managers were founder-owners of smaller companies. These use different criteria for decision making than managers in multinationals. The option to reframe some propositions, possibly taking this distinction into account, is discussed in section 6.4.

One aspect that did more clearly emerge from the research, including the empirical part, was the relevance of more long term oriented thinking, if managers are to take decisions that are beneficial for this longer term. The discussion on recognising the relevance of assessing the scaling potential relatively early in a process springs to mind. It remains difficult to gauge how interested or open managers in organisations that host design students really are with regards to this longer term perspectives. Small companies are usually in (short term) survival mode and large companies more often than not do not yet have accountability metrics that encourage this longer term perspective. To end on a positive note: times are changing, so the prevailing management sentiments on how to better mix short term and long term performance and accountability might as well.

6.3.3 Methodological considerations: looking forward

The starting point for next steps, to be outlined in the final section 6.4, is the conceptualisation of CVD 2.0 as shown in figure 6.1 and Appendix A6.1, and the rest of the chapter up till this point. With regards to the use of methods, these seem to be the main pointers to take on board for next steps:

- It is doubtful for three reasons whether there are propositions from this thesis that lend themselves for a deductive hypotheses-based approach in the next stage of research: 1. Hypotheses require a level of experience and mature theories that allows for formulation of substantiated relationships between existing theories. We are not there yet. 2. Few expectations with regards to this theme deal with such direct cause-effect relationships that these can easily be formulated in the form of hypotheses and 3. Empirically it is difficult to generate large enough data sets, with control groups, referring to fully comparable *real-life* situations, that are required to *test* these hypotheses. Each situation in real design practice, even in an education setting, is likely to be different from the next one in non-trivial ways.
- The suggested improvements in the conceptualisation of CVD 2.0, as well as the other modifications in the framing and communication as proposed in figure 6.1 and the Abstract in Appendix A6.1 could not be tried out on new audiences in terms of whether it improved their (speed of) comprehension because not much systematic historical data is available on comprehension of the two-pager on CVD 1.0. With the basic relevance of CVD for the design engineering domain for now established (as argued in 6.2), by now it does seem to be more fruitful anyway to inquire whether the modified framing and communication *does* resonate, instead of comparing it to the past.
- For design engineering education, one of the important attention points seems to be how encouraging students to use methods that explicitly acknowledge complexity can be aligned with supervision and goals. I.e. not making the outcome too fixed and allowing time at the start to look broader instead of immediately converging to a narrow design task.
- Ideally, at some point resources would need to become available to arrange longer term projects, i.e., with implementation in two or three contexts. This fully depends on long-term commitment from real-life organisations. Like with other lines of research, even then it seems to be more feasible to organise the projects in an absolute sense, with a goal to assess whether the results are “good” rather than in a comparative sense. For the latter type of project, historical comparative data would need to be present, available for disclosure

and representative, or parallel similar projects would need to be organised. This raises many barriers for setting up next research steps.

- Finally, and a topic that was not explicitly covered in the set of propositions in this thesis, it might be interesting to explore whether and how the thinking behind the CVD-approach is usable in other disciplines. It might be valuable to first informally engage with professionals from these different disciplines to explore which framing and terminology resonate with them. As promising example, though not executed in any systematic way until now, the conversations that resulted in a simple three-layer model of an adaptive architecture (figure 5.4) can be taken as inspiration. By engaging in dialogue with professionals of various disciplines, one way was discovered to effectively convey this part of the CVD-approach, i.e. the key defined construct of an adaptive architecture. Encouraged by these conversations, as further tentative broader exploration after the execution of the empirical cases in this thesis, the three-layer model was applied to results of a project outside the product design domain. The results are shown in Appendix A6.2. This represents a simple try-out, that might deserve more systematic next steps.

6.4 Not Knowing (yet) is an invitation to learn more

How do we take all of the above, contents and methodological considerations, and translate these into advice for concrete next steps?

6.4.1 Further suggested research: worth knowing more

Based on what we know, which areas of not-knowing are worth it to explore deeper in academic and/or practical sense and how? All research areas have implications for designers in practice and the potential to add new insights to be captured in academic literature as well. The suggestions point at relevant research areas within the main angles that were used throughout this thesis, they do not specify the concrete research questions.

Design engineering arsenal: "Revelling in richness". This thesis extended the notion of richness in the design space beyond the intuitive grasp and the most common understanding, i.e. use of several mediums. The results provide arguments and a basis to explore further. Comparative research may well be a part of this, i.e., comparing richness of design outcomes from differently structured design processes, but more as support for an even better understanding on how creating conditions that are conducive for richness might affect the eventual outcome in a positive way.

Sustainability impact on Scale: "Going for Gold". So far the long term benefit of using CVD, i.e. cost-effective impact at scale thanks to the adaptiveness of the architecture, have not been possible to verify because of time constraints and hesitance with principals of assignments to go all the way, It would be a valuable add-on research if companies and others would take these steps. This would require a multi-year commitment by the involved principals. Only if they commit can longer-term potential be verified in real-life settings. The other factors that influence scalability, like implementation capacity, market reactions and political blowback or support then become relevant as well.

Management alignment: "C'est le ton qui fait la musique". During the course of the research several notions have emerged that might be conducive for an environment where managers - who as rule rather than exception value a (high) level of control and predictability and as a consequence do not especially like complexity and novelty - give a new approach a chance. In particular this includes the openness, throughout the company, to mix short term and long term oriented metrics and accountability in a way that is more suitable for contemporary diverse globalised problems. For example: thinking in *time-to-markets (plural)*, considering the notion of *trending towards zero marginal costs* when aspiring implementation in different contexts, explicitly considering *inclusiveness of the range of requirements that is covered*, distinguishing short-term design unpredictability from medium term *clarity on the potential for scalability*, emphasising *averting possible losses* when sticking only to known methods vs highlighting the potential upsides of such methods, finding a right balance between bringing *contextual intelligence* together while leaving decision making *autonomy closer to the contextual fire*. This thesis has only scratched the surface of such aspects and framings and how they might affect the attitude of involved stakeholders. Follow up research could investigate such notions more explicitly, preferably in strong collaboration with a wide range of stakeholders. The latter would logically suggest that attention is required for framings that align with such stakeholders, like competitors and politicians, as well.

Design engineering education: "Leave no Leonardo behind". The empirical results in this thesis come from projects involving students. Therefore the conclusions should feed into design engineering education. As it turns out there are different ways how a more strategically and complexity oriented approach like CVD is experienced by advanced design engineering students. Some immediately see its value, others abhor or fear the non-prescriptiveness and apparent complexity. Further steps could be taken to test what type of guidance, supervision and conditions would be more conducive to take away this fear. Alternatively, since we cannot all be CEOs nor strategists, acceptance of CVD during formative years might be a kind of test that could potentially serve as indicator for the future role that a design engineering student can and should aspire to. The ones that do have ambition, and some talent, for more complexity-embracing roles can thus be spotted. Especially in those cases, educators might still need to encourage a mind-set of cooperation with people from other areas of experience and expertise.

6.4.2 Conducive conditions to learn more

This last section completes the journey for now by suggesting some (general) conditions that seem to be conducive for an environment in which learning can take place along the lines as suggested above.

Exploring what-if scenarios: In some cases it might be too early to test certain notions fully in practice, so practitioners would need to answer 'imagine-if' or 'what-if' questions. Outcomes of such questions in any domain need to be treated with some care because the gap between "saying" and "doing" is notably large. For example for the suggested research area with regards to (framing of) management considerations using face-to-face methods as opposed to for example questionnaires might be preferable, to get a sense for the level of understanding of practitioners with such terms.

A question of time. To stare complexity in the face and not blink, you need to have the available time to do so convincingly. The eventual end-to-end time needed to achieve satisfactory progress when executing a design task that acknowledged complexity might in some cases even be shorter than one that did not. However a high degree of time pressure at the start of the process, when nothing is clear yet, is not likely to create the conditions for a design engineer to make that happen: the pressure to put effort into achieving a quick, focused result is almost impossible to combine with getting a proper grasp of a complex situation, so this time needs to be (made) available.

(How) does size matter? It is likely, but not certain, that size and type of an organization has an influence on their perception and dealing with risks, uncertainty, metrics and so forth. Research can go in both directions in that sense: assume certain preferences depending on size and verify this. Or assume nothing and develop working assumptions for next steps based on the results.

Mixing money and impact. Likewise, results are very likely to vary, depending on the topic, on whether practitioners have sustainable impact in mind or not. Purely commercial considerations are different than considerations that combine business viability with sustainable impact. This is a 'variable' that very likely needs to be taken into consideration. Alternatively, for the time being, the purely commercial sector might be excluded from the next steps.

When -perhaps- not to bother. As a final point, building a bit on the previous one, it might be fair to conclude with stating situations in which "systematic variation before the final design task has been set", represented in this thesis by the CVD approach, would *not* be advisable. Such situations might for example occur if there really is very little time available to obtain good intelligence from multiple contexts, and/or it seems realistic to assess the design challenge at hand to be relatively simple. Also, there might be situations in which redesign that is required when moving to next contexts is a conscious strategy, e.g. if resources are abundant and a company wants to integrate the full learnings of pilots and does not mind the overarching inefficiencies. Thirdly, grasping and working with complexity does demand certain abilities and competencies, i.e. systemic, creative, imaginative, abductive ones. If the available design engineers don't possess these abilities then a CVD-like process might turn out to be too frustrating and therefore counter-productive. Finally if, as assessed by responsible managers, the expected differences between different contexts might be too big to consider them in an integral fashion to yield any synergies, this might be a reasonable argument not to do so full throttle and perhaps only as light-touch imaginative enrichment of the process.

A final thought: avoid drowning, help each other to swim

In short, there are many questions and considerations that design engineers, managers and others might have. The implications can vary when looking from an academic or from a practical angle. In the end this rather seems a luxury problem than one that blocks progress. This final section 6.4 provided a range of possible research areas and additional considerations, but is far from exhaustive. Readers should feel invited to add, question, enrich, and improve any of these suggestions on the journeys to come. In the end, encouraging inclusion of different perspectives and forging more cooperation is the only way in which this multiform society will keep making sustainable progress.

As a whimsical final thought refers to how I explain the core of Dutch DNA to non-Dutch people, with the historical analogy: "If we don't cooperate, we drown". In the past the drowning medium would have been water, in the present and future it would be the metaphorical ocean of complexity.

Chapter 7

Chapter 7 Epilogue: From Rags to Richness

This PhD-thesis started with a prelude that was written in a more personal and less academic tone of voice. This final chapter has the same characteristics. The academic part ended on the previous page. This epilogue is merely a personal addition, that therefore again has a tone of voice that is less formal than the one used in academic writing. You, the reader, are free to skip it if you have no interest in this personal deliberation at the end of this PhD-journey.

Admittedly, the title of this epilogue is (also) a word pun, but it was not chosen arbitrarily. Step by step the term "richness" has positioned itself as a key construct in this thesis. For that effort I reward it a visible spot in the title of this very final part of the thesis. To bring the whole document full circle, let's recap the main points in the same style as it all started in the prelude.

From the Bliss of illusionary control to variation-driven design Richness

The thesis is don, You, the reader, can relax now. Sit back and let's allow to percolate some of the main ideas one last time. After the dust has settled, what is it that defines CVD and what is it not? Do we, or rather more importantly, you, feel encouraged and if so confident enough to ask people to leave the blissful state of thinking that they are in control? While in fact if they are in control at all, this is at most in a very confined space. Amongst other things, this thesis was a call for letting go of much of the traditional sense of short term control and appreciate when and how not being in that state actually can have benefits.

All in all it is about making *well-informed, deliberate* choices that take into account both the short and *the long term*. Formulated in terms of the key constructs that were presented in this thesis: a *rich design space*, helps *designers and managers* to develop an *architecture for an inclusive sustainable globalisation*. This 'architecture' is not the only component of a strategy for achieving impact on a large scale. This was touched upon several times. The scope of this thesis simply cannot cover all of what is necessary and therefore only aims to provide a modest yet relevant contribution.

The points below might be further relevant starting points to guide near-future conversations.

1. First and foremost, to sidestep the discussion whether CVD is a philosophy, a method, a tool or something else, consider CVD as being a *mode of thinking* that is best invoked as early as possible when a design challenge might be coming your way. The later it enters the thought process the fewer benefits can be drawn from it.

This mode of thinking is best characterised by the statement: if you can foresee that your design challenge is (going to be) relevant for more than one type of context, do not fear this but face the challenge of complexity head on. Embrace contextual diversity and variation as keystones in your rich design space. Combine width with relevance. Zoom out first to have a much better idea where to zoom in. Take a wide-angle picture and then soak in what you have collected. By and large, this base attitude can be applied in all stages. If your resource pool is wide and relevant, you can dip into it more than once during later stages in the process.

One key point in the first stages is to not have rigid foregone conclusions along which dimensions the eventual contexts might have to be distinguished. The dominant dimensions that delineate contexts in a relevant way can vary per case, and the ones that provide the most fruitful basis for next steps may not be the initially obvious and appealing ones, like geographical borders.

2. Working in this way can and will make the formulation of the design task a more challenging one, with more considerations. That is not a bad thing!

The increased complexity of – possibly contradictory or out-of-comfort-zone – considerations is intentional. It is the surest way to force, or incentivise, a designer to look at the design space in different ways and invoke different, creative thinking to deal with the tensions. Without real-life friction there is only fiction. Without such encouragement there is every chance that earlier rather than later unconscious choices are made that prematurely limit the design space and set out invisible yet limiting pathways. Once you are on a road that is set it is difficult to leave it later. Path dependency, lock-in, heads down design are all recognisable symptoms of that scenario occurring. We don't really want that, especially if sustainability and basic quality-of-life "for all" are at stake.

3. The possible flipside of being highly aware of the risk of making premature choices is to not make choices, or much too late.

It is therefore very important to realise that not making choices at all, or 'infinite divergence', is *not at all* what is being asked of design engineers in these cases. Obviously revergence and subsequently convergence are called for. This has not changed from before. It is more the diversity and richness in each stage that is different than the general principles of Gathering information – Clustering – Making choices. When in doubt whether the transition points have been reached with sufficient attention for diversity and variations, it may in fact be better to first move to next stages and return later to gather and interpret more intelligence if these next stages reveal that essential pieces of insight are missing. Because you now have an open minded base attitude the chance that you will identify such gaps is quite big. It is part of working discursively and Living with Complexity instead of closing your eyes for it.

4. Put effort into aligning the dynamics of the *design space for designers* with those of the *decision space for managers*

If managers and designers are supposed to work together on tackling large-scale issues, it needs to be out in the open what the real metrics are that managers and principals in general work with, and are held accountable for. Their “decision space” as you might call it, is fuelled by different variables than those of a designer. If this is known to the designers, they can build a generative dialogue with the managers, and vice versa. When certain metrics, say *“shorten initial time-to-market´*, threaten the manager’s head like a thunder cloud but the designers are not aware of this, they will not understand the decision making dynamic that turns *their* design life impossible. Design flexibly and manage rigidly or vice versa, and it will not go well. Complete confluence of driving metrics is not necessary, but they should point in a similar direction. In line with the call made earlier for a better mix of short-term and long-term accountability, a culture of learning by doing (e.g. joint discussion on the problem to be addressed), and taking small steps (choosing relevant contexts), while keeping a larger picture (an architecture vs a ‘solution’) and longer term direction (inclusive sustainable society) in mind, will go a long way.

A major part of this transition towards a more adaptive overall attitude will be the ability of managers to recognise the limitations of wanting to fully control the process and the (short term) outcome. Instead, questions should be asked like “control what?”, “control to what end?”, and “is it really a bad thing if I don’t have full control?”. A useful nuance when insisting on the relevance of control might be to consider “more grip on the long term adaptiveness” to be an area to embrace.

5. Finally: how to embark on a wild multi-contextual journey? Where to look for guidance and what to discover yourself?

The main, and as yet quite general, advice to design engineers is: you are your own guide. Once the start is as has been championed in this thesis, i.e., you are consciously considering multiple types of contexts and are looking beyond obvious delineations for these contexts, many of the details on how to proceed are all yours. There is no blueprint on how to deal with complexity. This is both the positive challenge as well as a potential source of some trepidation. You can use the methods and tools you consider necessary, think in terms of double diamonds or less so, use all anchors from the rest of your design engineering arsenal that you find comfort in. In fact by all means find inspiration in the collection of tools and methods that are included in the Delft Design Guide 2.0 (Van Boeijen et al., 2020, rev. ed.).

As one last suggestion: do not concern yourself too much with the details of the design outcome until it is time to do so. The more preconceived notion you have about the result of your process, the less likely you are really open to being enriched by unexpected perspectives. If you notice that you are moving or being pushed into a direction too early stop and express this concern. Explain why this knowing where you are going early on may *seem* beneficial and then why it is counter-productive. “If you already know what you want to make, why investigate it in the first place”. If no one claimed that quote I’m doing it here.

And to make this thesis full circle, from title to epilogue: instead of insisting to know where one is going exactly and how one has to get there we might want to get our inspiration from Leonardo. He was probably the most explicit and productive, and yes, also gifted, example of someone who cared more about the inquisitive journey full of discoveries, driven by *systematic variations*. The problems we have to apply that attitude and method to may be larger and more complex nowadays, which may be all the more reason *not* to put an expiration date on this 500-year old ‘best practice’.

Appendixes

Appendix A2.1: Abstract CVD 1.0

CVD (Context Variation by Design) is a product/service development approach that has as a starting point that the complexity of contemporary society should be acknowledged and worked with to achieve better results. More often than not, a design challenge, specified in the design task, is (over)simplified to make it 'manageable'. In particular the focus is often on one use-context in order to respect the micro specifics of that context. This is tempting and seems sensible. However by severing the ties of the narrow scope of the design task with the rest of reality, such an approach is increasingly likely to result in solutions that have limited relevance and that cannot easily be scaled to new contexts like regions, countries, segments. CVD purposefully makes use of the reality of complexity instead of simplifying it away. The approach and associated mind-set includes a number of guidelines but is not intended to provide a step-by-step method or instructions. Many existing tools and design methods are available to designers to use and choose from, fuelled by the designer's own creativity. Prescribing the CVD approach by setting out exact steps would take away the designer's autonomy and creative freedom.

The key characteristics and associated benefits of CVD are:

- **Accept reality and make it work for you:** By being open about the reality that problems are not isolated to a singular context, the multiformity of the problem is respected. You get more diverse insights by connecting subjects (i.e., people and their insights) from the different parts of reality. In this way you build collective intelligence, instead of (just) very specific mono-contextual intelligence. After letting these insights interact in a 'shared solution space' you can still decide how to deal with conflicting or ambiguous sets of requirements. One can still decide on context-specific adaptations, but then born from an *intentional shared solution space* instead of born from one solution that was developed for and happened to be successful in one context.
- **The right problem formulation:** Having a mind-set that respects the reality of complexity enables you to recognise connections between a problem-area and the larger societal system E.g., "How can needs for electricity in areas with technically unreliable power supply be addressed in a way that is affordable for end-users and financially attractive for a company" as opposed to "How should we market product X in context Y to be profitable in Z years". The latter version considers society as an unambiguous, closed box. What some might perceive as strength (focus) is a crucial weakness: no eye for connections with broader reality and thus possibility of keys to the solution residing there.

- **Rich design space, not universal solutions.** The so-called shared solution space is not aimed at developing a 'universal solution'. Instead, a set of core insights on the problem, products/ services, segments, marketing and business model, partners etc. is achieved that benefits from the richness of the variety of inputs and interaction between these inputs. The result of this process can then be translated into actual solution concepts for one or more contexts. The eventual contextual variations of the solutions can be reflected in different parts of the overall solution, which can for example be modular (in/ out) or flexible (adjustable): functional features, overall design, but also communication, marketing, pricing, distribution etc. There are also likely *connections and synergies* between these variations that would not have been achieved without a simultaneous exploration. An obvious example is an intentional multi-context business model (e.g., revenues from version in one context cross-subsidise sales of same product in other context).
- **The main benefits**: 1) a rich solution space, 2) a superior base solution and 3) a cost-effective expansion (i.e. scaling or adaptation) to more contexts with *informed* contextual variations, working from that base solution space.

CVD-design principles

The CVD-approach uses four design principles that also interact with each other. Together they create a design dynamic that provides some guidance. The third principle is especially useful at the start of the convergence phase.

- Decomposition: address a complex design challenge by accepting the multiformity and distinguishing aspect systems instead of sub-systems. Breakthroughs for solutions will lie in the connections between different elements rather than in separating them.
- Systematic Variation: vary the elements of the problem and solution directions along the dimensions of product, market and network. Varying the actual decomposition is one, daring, example of such variation.
- Satisficing: acknowledge the limitations of "optimising" and undesirability of "compromising", focus on *satisficing* to create the starting point to build from to achieve the best possible result in the face of a variety of requirements.
- Discursiveness: acknowledge the multiformity of the situation in time, by allowing jumps and turns in the process instead of only steps and iterations.

A Management approach to match

To be able to work in the way as described, the (project) management approach needs to be aligned. In practice this means that especially in the first stage, when there are many uncertainties, project arrangements need to be such that:

- Respect that complexity implies unpredictability; design the process so intent is used as guiding factor so uncertainties do not cause negative distraction.
- It is realised that people make or break the eventual success (i.e., successful innovation requires much more than a product push).
- It is useless to set 'smart' targets if you have no knowledge to base these on.
- Dialogues about identifying the best options should be generative instead of transitional (convincing others of one reality).

The main concerns addressed

Based on reflection of design researchers and practitioners on CVD so far, a few recurring concerns have surfaced. We address the main ones here:

- Q: *Is CVD an attitude or a method*? A: CVD is best considered as an *approach and general mind-set* on how to tackle complex design challenges. It makes some intuitive notions more explicit. With more experience, more practical guidance can be provided. Detailed instructions kill creativity however.
- Q: *How do you know which contexts to include, when to stop diverging, how to let insights interact and when to start converging*? A: these are valid questions. Experience shows that practical aspects like company ambition, time allowed and motivation of the team highly influence the answer. Including 2 or 3 contexts instead of just 1 already adds much value.
- Q: *will the extra time needed at the start be feasible in practice? Managers, investors and small companies won't like this use of extra resources, nor the risk of uncertainty*. A: if you are aiming at developing a solution direction that can be scaled, adapted or replicated across contexts, eventual costs and risks of a *sequential* process will be even higher. Acceptance of a higher use of resources at the start depends on the ability to see the bigger picture. CVD appears to have most added value for developing new concepts, it is less relevant for simple line extensions.

Appendix A4.1: Longlist of available real-life situations

This overview shows the collection of available real-life situations that complied with the criteria in section 4.1.1. The references to academic peer-reviewed publications, if available (4th column) use the sequence numbers that are provided in table A4.2 in Appendix A4.2. The numbers in the 5th column refer to the propositions as listed in section 3.6.2. Many of the reports of these assignments are not easily accessible, some of them confidential, and most of them do not belong to the final case-selection. For these reasons, the full details are not provided here.

#, Type	Year	Description	Paper(s)	Related Propositions
1, Deep, group	2015	Mobile sanitation in India	2, 4, 6	1, 2, 6, 10
2, Deep, group	2015	Energy sharing in India	-	8
3, Deep, group	2015	Circular diapers for children with multiple handicaps in Bangladesh	2	1, 2
4, Deep, group	2015	Cook stoves Uganda and South Africa	2, 6	1
5, Deep, group	2015-6	Cook stoves Rwanda (desk) and South Africa	2	1, 2, 4, 10
6, Deep, group	2015	Floating community service centres Philippines	2, 9	1, 2, 6
7, Deep, External	2016	Scaling pilot-success: “Smart is not always Wise”-case (NDA)	6, 8	5, 6, 7, 9, 10
8, Deep, graduation	2016	Maternal health care device for Africa (Ghana) and Europe (NL)	1, 4, 6	1, 2, 3, 4, 6, 7, 9, 10
9, Deep, graduation	2016	Cook stoves Cambodia		1
10, Deep, group	2016	Cook stoves urban and rural Vietnam	3	2, 3, 4, 5, 8, 10
11, Deep, group	2016-7	Cook stoves Cambodia		1
12, Deep, graduation	2017	Health diagnostics		1, 8
13, Deep, graduation	2017	Insects as food stock in Asia & Europe		1, 2, 4
14, Deep, graduation	2017	Charcoal cook stove Uganda and Ghana	5, 6 ,9	1, 2, 3, 4, 5, 6, 7, 8

15, Broad course	2015-2017	Comparison of experiences (and results) by students with and without contextual variation	7	2, 7, 8, 9
16, Broad, course	2018	Level of desired instructions for new tools and methods	6	7, 8, 9
17, Deep, graduation	2018	Seaweed applications NL and Caribbean		1, 2, 4
18, Deep, graduation	2018	Health diagnostics African countries		2, 10
19, Broad, course	2018	Introducing novelty in a course		8
20, Deep, graduation (non-IDE)	2018	Single use Plastics in Indonesia		2 Non-IDE input
21, Deep, graduation (non-IDE)	2018	CVD applied to process flow for pump placement		1 Non-IDE input
22, Deep, graduation	2018-9	Multinational, strong lightweight waste material		1, 2, 4, 5, 8
23, Broad, graduation evaluations	2017-9	Extensive evaluation of diverse IDE-graduations (12, 13, 14, 17, 22)		1, 2, 3, 4, 5, 6,, 8, 10

Table A4.1 Longlist of available cases

Appendix A4.2: From longlist to cases

To get from the longlist to a feasible number of cases, amongst others the extent to which real-life situations covered the areas that were captured in the propositions, and the extent to which they were included in academically peer-reviewed publications with the PhD-researcher as (co) author were determined. To whomever is interested, the result of this intermediate step is shown in the two tables below. The result of these steps was a reduced longlist of eleven (11) potential cases. The further reduction towards the seven (7) eventually selected cases for this thesis was based on differences in available quality of information and compliance with the criteria on portfolio level.

#	Year	Type and source	Touchpoints with propositions
1	2016	Conference, Norddesign	1, 2, 3, 4, 6, 8
2	2017	Journal, Procedia Manufacturing	1, 2, 4, 5
3	2017	Journal, Sustainability	1, 2, 3, 4, 5, 8 (10)
4	2017	Conference, RSD6 (DRS)	2, 3, 8, 9
5	2018	Conference, GHTC (IEEE)	1, 2, 4, 5, 6, 8, 9 (10)
6	2018	Journal, Formakademisk	2, 3, 7, 8, 9
7	2018	Journal, J. of Design Research	2, 4, 8, 9
8	2019	Book chapter, *Transitions to a sustainable society*	7, 9, 10
9	2019	Peer reviewed working paper	2, 4, 6 (10)

Table A4.2: Academic publications and their touchpoints with Propositions

# from Longlist, Type	Year	Description	Paper(s) from T 4.1	Other argument
1, Deep, group	2015	Mobile public sanitation	4, 6	
5, Deep, group	2015	Cook stove (value chain)	2, 6	
6, Deep, group	2015	Community centres with WASH facilities	8, 9	
7, Deep, external	2016	Renewable energy in emerging economies	6, 8	(1)
8, Deep, graduation	2016	Maternal health care	1, 4, 5, 6, 8, 9	
10, Deep, group	2016	Gasifier cook stove	3	
14, Deep, graduation	2017	Charcoal cook stove	5, 6, 9	
15, Broad, course	2015-2017	Comparison of experiences with and w/o context variation	7	
16, Broad, course	2017	Exploring desired level of instructions when introducing novelty in a design course	6	
21, Deep, graduation, non-IDE	2018	CVD mindset applied in non-IDE setting		(2)
23, Deep and broad, graduations	2017-2019	Comparison of experience of graduation students		(3)

1. Case with strong managerial component, and thereby relevant for the associated propositions
2. Conceptually interesting to consider how non-IDE students deal with a design-inspired method
3. Only available case where broad and deep are combined

Table A4.3 Pre-selection of cases based on academic relevance for the propositions

Appendix A4.3: The other selected cases

This Appendix contains the detailed descriptions of cases that in table 4.1 were identified as #1, #2, #4, #6 and #7. The same format is used as for case studies #3 and #5 in the main body of the thesis. Where relevant, specific sections in relevant external publications are referred to for traceability of methodology and original data.

Case #1: Maternal health care device, Deep (graduation)

The main – somewhat stylised – results of the case as well as the full process of the experiment that is described below is included in Ref #1. Other discussions of this case through an academic lens as part of the PhD-process were published in Ref #4 and Ref #6.

A. Description of the case (contents)

<u>Topic and timing</u>: This case study concerned a graduation assignment of an MSc-student conducted in 2015 and 2016 within the theme of maternal health care in distinct contexts. The chosen localities were Ghana (with medical professionals of various skill levels as end-users) and the Netherlands (with expecting parents as end-users). The principal was a small-medium sized company located in the Netherlands which had contacted IDE to recruit a graduation student and was open to the idea of an intentional multi-context approach, although their initial idea had been to let the student focus on the Western context.

<u>Expected results:</u> The principal expected a clear advice how to adjust a provisional prototype so it could be effective in several contexts. They also, less articulated, expected some preliminary insights how to develop a multi-context business model. The student had to take into account an actual existing but relatively rudimentary prototype and could not physically alter that prototype as part of her assignment. She was allowed to materialise the advice in a physical mock-up and digital rendering.

<u>Process highlights:</u> As methods for data collection and assessment the student used a literature review, interviews with stakeholders in both contexts, field visits (to Ghana) and creative sessions in the Netherlands.

Within the limitations regarding time and resources it was not possible to have parallel design processes for mono-contexts (2) and the shared design space (3) separately. This would also have been far beyond the scope of a graduation assignment. For the purpose of the PhD-research, but with expected benefits for the graduation student as well, an experiment was conducted mid-way with links to several propositions. This experiment is described in section B, the results included in different observations related to propositions, in part C.

Final result: The process and results of the design assignment itself are published in (Van Gils, 2016) and aspects of it are included in the publications that are mentioned at the start of this case description.

B. Relevance for this thesis and research questions

The PhD-researcher acted as second graduation supervisor, mostly as interested observer without influence on actual design choices.

In order to generate more added value for the PhD-process, one of the general design process steps (from insights to concepts) was used for an experiment that would allow for some comparisons between mono-context and shared-context driven design and thereby create explicit insights that were relevant for several propositions but did not fundamentally alter the design process: after the lead designer had composed shared insights, three groups of students with a similar composition (age, gender, study backgrounds) each received a set of insights (context 1, context 2 or shared) and the same design brief representative for the one that the graduation student had received, and were asked to generate design concepts. The location of this CVD-driven experiment in the design process as a whole is shown in the figure below:

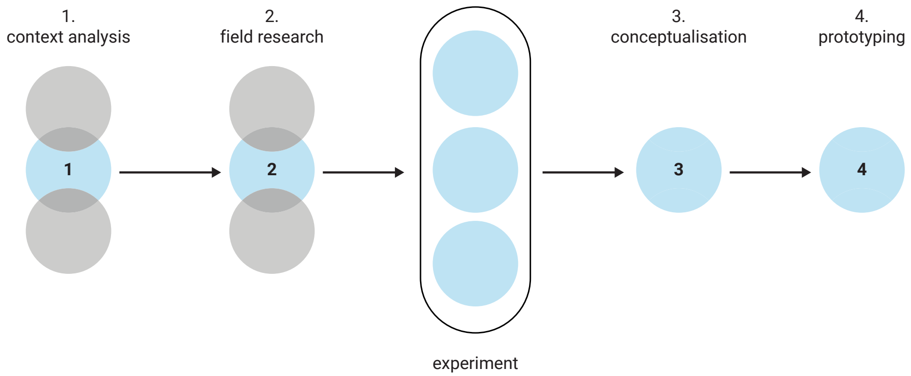


Figure A4.1 CVD-driven experiment during design process

The following assessments, including by seasoned design experts, were then performed and aimed at creating a multi-perspective picture of the similarities and differences between the settings (context 1, 2 or shared):

1. The students peer-reviewed all concepts in terms of *creativity* by indicating which elements in the design concepts of the other groups were surprising (positive or negative) and which elements they would have liked to have thought of themselves. The PhD-researcher afterwards labelled these comments as negative, neutral, or positive. This allowed, per design concept and session, an overview of total scores and how the positive and negative comments were divided. This served as proxy for an assessment for the peer-assessed creativity.
2. The students were also asked to reflect on the *process in their session to create three design concepts* in their group; these comments served as enriching input to create an overall picture about the extent to which the shared insights influenced the discussion within the group as compared to the groups which had received mono-context insights. Note that none of the students were presented with these terms, they only had the set of insights they received and the design task to work with.
3. Three detached design experts from inside the faculty – without knowing which concept belonged to which group – assessed the *richness* of the design concepts, nine in total, on a scale from 1-10 and they all intentionally used their own interpretation of this notion.
4. The lead designer (graduation student) who did not get involved in the concept generation, assessed the *relevance* of the concepts for her assignment by giving each concept a mark between 1 and 10.

The full results of all these assessments 1 to 4 are included in sections 4.1 to 4.4 of Ref #1, specific aspects are used and discussed in more detail in part C below.

The results of the experiment were inter-subjective because of the use of different design experts who assessed richness of intermediate results (3), student peer-reviews (1 and 2) and opinion of the lead designer (4). The labelling of the results of the creativity comments (1) was done by the PhD-researcher.

The lead designer (graduation student) was free to use all results of the sessions, but eventually primarily used the ones from the shared session as stepping stone for her eventual concept direction and suggested improvements to the principal.

C. Findings related to the propositions

In terms of the Propositions, these are the main findings:

For proposition 1: unanticipated insights are likely to be created in a shared design space

- Both in the student-group experiment as well as in the full assignment, several examples can be identified of shared insights that would have been very unlikely if the design would have been based on a deep-dive in either of the contexts. Of particular interest are 1. insights that were created by 'injecting' a specific remark from a conversation in one context into discussions with stakeholders in the other, thereby creating cross-fertilisation, and 2. Insights that need to be combined to create an overarching insight that is relevant for major design choices.
- One of the most striking design choices was the decision to separate the hardware (device) from the software. Almost all differences between the contexts could be captured in the software. This would on the one hand make the device simpler and easier to produce. On the other once intelligence is allocated to the software, it immediately opens the door for more easier to develop and implement variations. Without combining the research for different contexts, this insight by the designer would not have been impossible but there would not have been any driver for it.

For proposition 2: a rich design space leads to well-informed choices

- The 2nd insight under proposition 1 reflects a prime example of how a rich(er) design space leads to well (better) informed choices, that are by all means relevant for next steps.
- Students in the shared insight session of the experiment conveyed that they valued the discussion more than the eventual concepts; students in the other sessions did not mention this. The former group also considered their concepts quite shallow, the others thought their own concepts were reasonably worked out. Still when asked to assess all concepts on *creativity* (originality and "would like to have thought of that") when subtracting the number of remarks that were labelled as negative by the researcher from the positive ones the totals from the former group scored much higher (10.3 average score, vs. 6.7 and 1.3; table 1 in Ref #1).
- The collected *richness* assessment data revealed one overall pattern: the richness of the concepts that were generated in the session based on the shared insights were higher on the level of single concepts and cumulative (6.0 vs 4.9 and 5.0; table 2 in Ref #1). The first set of concepts scored considerably higher in terms of peer-assessed creativity, and the lead designer considered the concepts from the shared insights-session more relevant (7.0 vs 6.3 and 6.3; table 3 in Ref #1).

- The assessment of the lead designer of the results from the shared insight session were higher than the assessment score of the experts regarding the richness. This might be an indication that besides the 'technical' richness, the concepts contained additional, less obvious elements that might typically emerge from a rich discussion.

For proposition 3: a shared understanding of the concept of richness can help to grasp a complex design challenge

- The experts used their own interpretation of richness. This was done on purpose by the PhD-researcher to let them think consciously about what they individually considered to be the essence of this intuitive construct. That essence ranged from "holistic" or "conveying a deeper thought" to "still express a sense of feasibility". Most importantly the experts all considered richness to be a construct that cannot easily be captured in one term and expressed to have liked explicit guidance on the intended interpretation. They expressed that relying on their own interpretation was not conducive for creating a comfortable assessment environment.

For proposition 4: considering multiple use cases contributes to an architecture mind-set

- The earlier mentioned overarching insights (proposition 1) also provide a productive basis for architecture decisions as opposed to single optimised products.

For proposition 6: multi-contextual design spaces are likely to result in (more) inclusive results

- As argued in Ref #9, by explicitly combining requirements for a context for which the effect would represent social impact with one where the device is more a luxury item, the financial viability of the overall effort increases. Thereby the *inclusiveness* of the effort increases, one might say indirectly compared with the scenario when the former would be the only use-case. In the latter case the company that produces the device would most likely settle for a fully donor-funded business model.

For proposition 7: to perform well in a complex design challenge, the (business) environment has to allow a high level of unpredictability of the outcome.

- Based on comments by the students, it seems that even while explicit consideration of multiple contexts makes the discussion more complex, they can recognise that this complexity has a purpose and that it makes the discussions more interesting.

- The reflection furthermore revealed that having more specific information available about the context, use-case, intended target-group would *not necessarily* have improved the concepts. Having more certainty early in the design process rather seems to close off pathways than help the process, as several students shared in their reflection.

For proposition 9: willingness to embrace external complexity is influenced by fear of internal complexity, i.e. the process resulting in a complex high-tech product.

- While all groups were made aware of the relevance of multiple contexts, the groups that were only provided with mono-context insights did – by their own admission – not do much with that part of the design brief. This seems to indicate that they did not take the multiformity of the design challenge seriously, potentially because they feared the complexity of doing so.

For proposition 10: if decision makers think in terms of time-to-market**s** (plural)**,** they may allow a higher initial effort to include a wider diversity of requirements.

- The principal implicitly allowed in the design brief that the higher initial effort, i.e. explicitly investigating multiple very different contexts, was allowed. In part this approach was expected to generate potentially beneficial insights in terms of the business case.

Case #2: Gasifier cook stove in Vietnam, Deep (group)

A part of the results as described in this case have been extensively published in Ref #3, Open Access. Where relevant, this paper and specific parts therein are referred to in the description below. All data can be found there as well.

A. Description of the case (contents)

Topic and timing: This case study concerned a group assignment of four final year MSc IDE-students that was conducted in 2016. The application are was gasifier cook stoves with manifestations in rural and urban Vietnam, which represent two distinct but potentially connected contexts. The principal for the assignment was an organisation in Vietnam with Research & Development and commercial departments. It had been developing a range of gasifier cook stoves for the five years preceding this assignment, with different variations, but each effort always had always been geared towards one particular context/ use-case. The principal was well used to working with IDE-students and was specifically interested in a group that could work on a version that would be suitable for multiple contexts.

Expected results: The desired and expected result for the students and the principal was a testable prototype for performance comparison with previous versions. As a spin off the project was supposed to provide in-depth insights on the richness of the conceptual design space, in the form of the sets of insights that were obtained in the design process (see part B).

Process highlights: During the assignment the student group used a variety of data collection methods, with own observations and interviews with end-users and other stakeholders being the main ones. This resulted in insight cards per context (urban and rural). The rest of the results then built on these data.

Final result: The student group did deliver a testable prototype for which requirements from both urban and rural contexts had been taken into account. Even more, they designed the outline for a business model where the two types of contexts would be connected and provide synergy. The outlook of a viable business model would eventually be crucial to encourage further development towards actual production and adoption.

The performance of the prototype was assessed and tested on 52 different indicators by the principal after the assignment has been finished by the students. The results referring to this performance scoring of the prototype compared with four previous gasifier stove versions by the same principal has been extensively described in Ref. #3. The results in terms of the characteristics of the developed prototype itself are covered in Appendix D of that paper. For the purpose of this thesis these detailed characteristics are not of major relevance, since it would take in depth technical expertise about gasifiers and cook stoves to appreciate that information.

B. Relevance for the thesis and research questions

The PhD-researcher acted as informal supervisor for dialogue with the students, without any influence on interpreting insights and actual design choices. The prime role was as neutral facilitator during the phase where mono-contextual insights were shared and discussed within the group.

More importantly, the PhD-researcher coordinated the performance scoring process of the prototype which included finding relevant experts to score different (historical) gasifier stoves in one consistent manner, to be able to compare these historical assessment scores with the most recent one. The main criteria for this experts were: expertise in the main areas (Vietnam, gasifier cook stoves, and/or industrial design aspects), no active involvement in the project to prevent bias, and availability during the period of assessment. The results of the entire performance assessment process were in favour of the most recent one that was developed using the CVD-approach. More detailed results are included in section C of this case description, mainly related to proposition 5.

This particular project also was suitable to conduct an advanced test for proposition 3: after constructing an agreed working definition of the multi-level construct of “richness” the PhD-researcher coordinated the assessment of richness of different intermediate design results during this process. To execute the richness assessment, the group of four students was first divided in two times two; one group performed the rural context investigation, the other one for the urban context. They both captured their main findings in a set of ten insights. Next they combined their findings in a shared design space, yielding a third set of insights. These three sets provided the basis for a comparative assessment of “richness”, both on insight and set of insight-level. The detailed process of creating all richness scores might be published in a paper. For now it is therefore not opportune to explain the entire scoring methodology in detail. The most important data, i.e., all assessment scores for richness, are however included in Appendix A4.4. The main results are included in section C of this case description, mainly related to proposition 3. The assessors of richness were the team of design students (together), and two detached experts from the IDE-faculty who - to prevent any possible subconscious nudging – were not told about the contexts, separate sets of insights etc but just asked to assess all insights (31 in total) using the three-part working definition. The detached experts had been selected based on the criteria of non-involvement with the project and knowledge about the topic (gasifier stoves in non-Western context).

Both assessments – performance and richness – were expressed in actual comparable numerical scores, so no interpretation was required by the researcher, which means there was no risk of subjectivity. The assessment scores themselves were made inter-subjective by means of using multiple experts as assessors for both assessments.

C. Findings related to the propositions

In terms of the propositions, these are the main findings:

For proposition 2: a rich design space leads to well-informed choices

- Although individual projects in the past had yielded good insights and results for individual contexts, so the knowledge did exist, when intentionally putting such insights together a different decision making dynamic occurred, as expressed by the principal. Having all information in the same place, physically and conceptually, created more overview and opportunities for spotting new patterns and connections between the contexts.

For proposition 3: a shared understanding of the concept of richness can help to grasp a complex design challenge.

- Based on some groundwork on the construct of richness, that was touched upon in section 3.5.3, a working definition of the multi-level construct of richness was developed. This working definition identifies three aspects that can be assessed: a unit of analysis is richer the more it 1) represents multiple views 2) is generative and 3) refers to connections between elements instead of just the elements themselves.

- The workability of this three-part definition has been tested and confirmed on the level of "set of insights": both contexts (rural and urban) and the shared context were captured in 10-11 insights each. The pattern of assessment scores for individual insights was scattered ("chaos") but when clustered per context one clear overarching pattern emerged: for each of the three assessors there was one clear set of insights with on average the highest assessment scores: the highest scoring set of insights referred to the design space where insights from the two individual contexts had been brought together.
- The involved assessors confirmed that the three-part working definition gave them more guidance than having to interpret the term richness themselves.
- One angle to assess the added value of having a three-part working definition, and assessing insights as opposed to for example one overall result is to identify whether there are notable differences in assessment scores between the insights and between the different aspects per insight. As can be seen in the scores each assessor did score aspects (= parts of the working definition) of the same insight quite differently, as well as scored different insights for the same aspect substantially different. In short: when given the possibility to distinguish in scoring (assessing) the assessors did use that opportunity. Thereby such nuance seems to add more depth to allow a 'rich' overall assessment to *emerge* as opposed to having to address such an assessment in one overall score that hides all nuances.
- The value of having a shared definition as opposed to each designer using an intuitive notion of this construct was not explicitly investigated in depth. Based on first discussions, that value may lie in speaking the same language when assessing tentative results in the design process ("Did we capture the landscape in its entirety") and leaving less room for misunderstandings. At the same time, being able to explicitly assess three different aspects provides more room for nuance in such discussions than one score that averages many aspects and thereby hides valuable information.
- The three-part working definition has not been tested on prototype-level because resources did not allow development of three prototypes (two for each individual context and one for the shared context), especially because two of them would likely not be used in practice. The whole point was to develop a version that could cater for both contexts.

For proposition 4: considering multiple use cases contributes to an architecture mind-set

- The result – a multi-context prototype and business model - explicitly incorporated a rough business model design that used the interconnections between the contexts. A business model can be considered as part of the "architecture".
- By considering an integrated business model, aspects that had thus far been a problem, e.g. waste streams from the gasifier based cooking process, could now be turned into an explicit component of an overarching business model.. The architecture-mindset extended beyond the product design, even though the business model was not part of the performance assessment.

For proposition 5: design outcomes following CVD-mindset potentially have higher performance

- The main goal of this assignment was to develop a prototype that was suitable for rural and urban contexts and demonstrably performed well compared with previous versions.
- To that effect the prototype was assessed on 52 indicators, divided in nine categories and compared with the scores of four main versions from the recent years. The detailed account of this entire assessment process is captured in Ref. #3. Three experts in the fields of cook stoves and design contributed to the process, the fourth one was the principal who coordinated the assessment (see table 1 in Ref. #3).
- After consultation with the three other experts the principal made the assessment of the new prototype, it was compared with four previous main versions (table 2, Ref. #3) and more in detail with the previous three (table 3, Ref. #3).
- Even when taking into account the 'autonomous learning curve', i.e. the historical slope of the aggregated performance score (increase), the prototype that was developed based on the CVD-approach scored substantially higher (10%) than if it would have just followed this historical learning curve. In other words, the performance assessment score demonstrated a jump. This is visualised in figures 1 and 2 in Ref. #3.
- When zooming in, none of the (9) overall category assessment scores was lower for this prototype than for previous versions, some showed a considerable jump. All scores for the four historical gasifier stoves can be found in Appendix C of Ref. #3, the scores for the CVD-driven prototype in Appendix E of that publication.
- The set of indicators did not include business model considerations because these were not included in the historical assessments either and it was not possible to do this in hindsight. These would have represented one main improvement-area for this version that would

have pushed up the score even more because the design allowed for certain contextual interactions with a positive effect on the business viability.

For proposition 8: willingness by design engineers to embrace complexity implies not demanding or needing detailed instructions.

- The students received guidance on conceptual level and encouragement of the supervisor especially in the phase of bringing the contextual insights together. This took the form of facilitation of the session, without any intent to influence the contents. In other words, the students themselves took charge in discussing and identifying possible patterns and thereby shared insights, as well as translating these to the prototype design.
- Instead of expecting a manual with instructions for this process, a pragmatic bottom-up manual with rough tips and observations on the process was constructed.
- It seems relevant to note that the students volunteered for this particular assignment and thereby with eyes wide open entered a process with fewer landmarks in terms of design methods. They seemed to be predisposed to not acting out of fear of the unknown.

For proposition 10: if decision makers think in terms of time-to-market**s** (plural), they may allow a higher initial effort to include a wider diversity of requirements.

- The principal did consciously allow more resources to be spent in this assignment compared to several previous ones (i.e. four students vs just one) but this did not have any financial consequences. It is therefore not easy to say by now whether this decision conveyed a real willingness to allow “higher initial efforts”.

Case #4: MSc course development, Broad (course)

A detailed account of this case study is published in Ref #7. In some places below, specific supporting data that is published in this paper is referred to.

A. Description of the case (contents)

<u>Topic and timing</u>: A mandatory MSc-level course that concerned Internationalisation as part of the design profession, with a focus on emerging markets, was especially suitable to introduce CVD. In subsequent years (2015 and 2016) the CVD-approach had been presented, including emerging examples. In the first edition (2015) the students had to do a small (reading) exercise and provide their open comments. In the next edition (2016) the student groups as a last assignment had to take on a design challenge that did not explicitly encourage CVD, followed by a very similar assignment that did and were asked to reflect as a group on this paired

experience. The course edition that this case study refers to (2017) was the last one in that form, intended for students for whom it was still mandatory but who had not followed the course in a previous year. The set-up of the CVD-part of the course was similar to the one in 2016: one lecture and a pair of similar assignments, one with and one without CVD. The reflection was however more structured (survey) and done individually. Student groups could decide themselves on the exact area or brand they wanted to work on. It had to be an existing brand, but they could then zoom in on a new application area for that brand. In other words, the situation was realistic but not already existing.

<u>Expected results:</u> The main results were expected in the area of insights on student perceptions and experiences of executing a similar assignment first without and then with CVD and whether the latter added anything to their arsenal. By making the format more structured and asking the students to do the evaluation individually, the results were expected to yield more useful and potentially diverse results than a fully open one on group-level. The responses indeed varied between students within the same group. The assignment was very short, and the actual design results were not of primary interest for the research apart from the reflection by the students themselves. To still give some idea about the differences in the actual concepts, three examples are included in Appendix 2 of Ref. #7.

<u>Process highlights:</u> The evaluation consisted of two parts: a closed part where students had to indicate for fifteen design process aspects whether using CVD-thinking encouraged (much) more, the same or (much) less of that aspect compared with the same assignment for which they had not used CVD. Like mentioned in the description of case study #5, the list of aspects for this evaluation survey had been the result of dialogue with IDE teaching staff and students, based on previous experiences with complex design challenges, fuelled by relevant contents from the literature search. More details are not ultimately relevant for now and are included in section 3.1 of Ref. #7. The open part allowed them to reflect more elaborately on the differences (if any) and added value (if any) of using CVD in their design arsenal on contents and process level. The evaluation was anonymous and not part of the grading process of the course. The overall results and patterns were compared with a-priori expectations based on literature and previous experiences.

The fifteen design process aspects for the closed part of the evaluation were carefully put together based on evaluations of previous versions of the course. The choice for a semantic differential with five options (much less, less, same, more, much more) was based on the felt necessity to allow for some depth (i.e. three options are not enough) and the realistic and relevant value of “same”. In other words, while offering the option “same” as middle option and thereby providing a 'safe' choice, this was not sufficient reason not to include it as opposed to just allowing four options (much less, less, more, much more).

Final result: The evaluation was completed by 32 individual students, who had worked in nine separate groups. Of the 32 students, based on their responses 19 were identified as having an overall positive opinion of the use of CVD, 8 neutral and 5 negative, as can be found in table 1 of Ref #7. These latter five all came from two groups. Detailed responses within these groups however varied. This demonstrates the added value of individual reflections (distinct opinions) over group reflections (average, compromise).

Of the 480 assessment scores (15 aspects * 32 students) in the closed part of the evaluation, in 29% (140) of the cases the middle option was chosen ("same"), 56% the options one from the middle ("somewhat less", "somewhat more") and 15% the extremes ("much less", "much more"). This seems to enhance the relevance of the results, in the sense that 7 out of 10 scores (or 71%) indicated a difference in the experience when using CVD or not. The details of the scores can be found in table 2 of Ref. #7.

In their answers to the open questions, the students handed in a total of 48 distinguishable comments, ranging from deep or thoughtful to short and shallow. That in principle seems a realistic diverse result for a mandatory evaluation. All comments can be found in Appendix 1 of Ref #7.

When comparing the results and patterns therein with a-priori expectations, in most cases the two corresponded. The strongest difference in the reflections in favour of CVD was the aspect of "Revealing hidden connections". Another interesting outcome was that 19 out of 32 students considered the outcome of the CVD-driven assignment to be of higher quality than the similar assignment without CVD. The a-priori expectations with regards to the downsides of CVD (higher mental effort, overwhelming, less simple) were also mostly confirmed. Although the expectation of CVD being more overwhelming was far less strong that expected. Finally, the results did seem to indicate a somewhat diffuse level of understanding of concepts like richness, inclusiveness and simplicity.

As overarching observation it is clear to see that while results are somewhat diffuse, there are no clear examples where the use of CVD was assessed as *worse* than doing a similar assignment without it. The one -minor- and expected exception was the perception of CVD being a more overwhelming experience. Another outcome was that CVD in the perception of the students leads to less simple and less simplistic results. These might however be terms that are easy to misinterpret.

B. Relevance for the thesis and research questions

The role of the researcher was to present CVD during the course, contribute the pair of similar assignments to the course coordinator (with and without CVD), develop the survey, tabulating the answers to the closed questions and coding the overall reflections by the students, and triangulating all student input to draw conclusions in the form of the observations in part C. As part of the publication of these results (Ref. #7), this triangulation was peer-reviewed internally and externally.

The primary method for data collection and assessment was the two-part survey. The answers to the open questions were coded negative, neutral or positive for even richer input for the triangulation of all responses.

The results were made objective by means of making the reflections anonymous, making a large part of the evaluation closed (= no wiggle room for interpretation) and coding the overarching gist of the open answers in rough categories (positive, neutral, negative) which allows for easier distinction and less prone-ness for biased interpretation. The validity of the results - including triangulation of all responses to the evaluation forms – was confirmed by the aforementioned peer-review as part of the publication (Ref. #7).

C. Findings related to the propositions

In terms of the propositions, the main findings are listed below. These are derived from sections 5 and 6 in Ref #7 and combined with the description above:

For proposition 2: a rich design space leads to well-informed choices

- The aspect of richness seems to be seen as a positive aspect of CVD if "revealing hidden connections" is also included. There still is some reason to believe that there is a range of interpretations possible of this term. Even so, evaluation of other aspects like "direction for inspiration" and "deep/ complete issue analysis" at least do not point in another direction.

For proposition 7: to perform well in a complex design challenge, the (business) environment has to allow a high level of unpredictability of the outcome.

- There does seem to be some room for students to start with unpredictable – and even uncertain - processes, and postpone the temptation of 'toolified' simplification of the challenge that in practice can lead to "heads down design" (Myerson) and "path dependencies" (Jones)

For proposition 8: willingness by design engineers to embrace complexity implies not demanding or needing detailed instructions.

- It might be a fact of life that thinking in reductionist terms and thereby "mutilating the very web of interconnections that weaves complexity" (Montuori) is part of any cohort of students, 'even' of advanced design engineering students.
- Most students however seemed to be open to some level of "complex and generative dialogue" and recognising the value of working with "mutual interdependency" (Thompson). This case did no go into the question, nor was it designed as such, whether this is something typical for design students or a more broader human characteristic.
- Experiencing immersion in a design process that is centred around generating richness might be a good step toward embracing complexity (Sevaldson).
- A sizable number of comments referred to the matter what type and level of detail of instructions might be in order when presenting a new approach to students. The responses to the open questions provide some direction for alternatives for such instructions, i.e. lighter forms of guidance that do not represent too strong simplification early on, but might be helpful in the sense of "highlighting the generative nature of complex dialogue" (Montuori), "emphasising generative sensing" (Sevaldson) and emphasising the complementary or even synergetic nature of CVD with other methods like Gigamapping (Sevaldson), rich pictures (Checkland), system diagrams, morphological charts.

For proposition 9: willingness to embrace external complexity is influenced by fear of internal complexity, i.e. the process resulting in a complex high-tech product.

- Based on responses to open questions (see Appendix 2 in the paper), the fear of accepting more complexity in a design assignment might become less if there is either more time to execute the assignment or there is more perceived freedom in 'wandering around' before making final choices. This points in the direction of reserving CVD for longer assignments, otherwise it might possibly be counter productive, i.e. stress inducing

Case #6: MSc course enhancement, Broad (course)

The main results of this case study have also been included in Ref. #6 (open access), in particular on page 22, point 3.

A. Description of the case (contents)

Topic and timing: This case was executed against the backdrop of an elective MSc-course that was given in the first half of 2018. An evaluation was conducted immediately after the final presentations had been given, all students who were present (eighteen) completed it.

Expected results: The course introduced approaches (including CVD, but also Gigamapping, system maps and others) and tools that were intended to encourage typical design-skills like using different perspectives and visualisation and apply these skills to relatively known contents (recognisable use cases). Instead of providing very detailed instructions, the students were given minimal introductions about the tools. The survey was intended to reveal to which extent, in hindsight, they considered this low-direction approach to be desirable. The set-up of the course had on purpose been changed from the past editions where novelty of cases was combined with relatively known tools.

Process highlights: The participating students were introduced to a number of visualisation and complexity-related design methods, including CVD, Gigamapping and system diagrams. On purpose they were not bombarded with details and instructions but just the main points and aims. The four student groups were free to decide which of the newly presented tools and methods they would actually use during their group assignment and how.

The students were free to use any way to collect information and bring it together in a report, complemented by a presentation on how they has used which methods to shed light on their case.

In the evaluation afterwards the students were specifically asked about their experiences with using CVD (general approach) and Gigamapping (tool). The gist of the results was similar, in this case study description the focus lies on CVD.

The questions focused on their understanding of these methods before and after using them, level of enjoyment, extent of having received sufficient instructions and whether they saw themselves using the methods again in the future.

Final result: The actual design results of the student groups are not relevant for the case study, only the results of the evaluations are. As expected, and intended, the appreciation of the students of the level of instructions was not very high, 6.1 on average. Still, 2/3 of the students awarded a 7 or higher both for the question whether they enjoyed the use of the CVD-approach, and whether they saw themselves using it in the future. 2/3 of the students also responded to have understood CVD better after using it scoring on average 7.5 after and 6.3 before with virtually all students following this pattern.

B. Relevance for this thesis and research questions

The role of the researcher was to present CVD in a lecture, design the survey, code the survey results, interpret the results and translate these in conclusions for the paper, and the thesis. The survey, see more details below and in section C, did not have any influence on the grading process. The staff members involved in the grading did not see the survey results.

The survey consisted of a closed part (five questions where students had to indicate between 1, not at all, and 10, very much, to which extent they agreed with the statement) and open part (four elaboration questions). The evaluation had the form of a one-page hardcopy.

The closed part served as input for an easily comparable assessment, which was combined with the more qualitative data that were provided by the responses to the open questions. The results were not intended to be statistically oriented but more on the level of identifying patterns. The answers to the closed part were fully objective. The process of combining these responses to the open questions might have a level of subjectivity in it, but since the patterns were discussed in a general manner and interpreting them occurred in dialogue with design experts and students, this at most only has limited impact. More-over, imaginative (inter)subjectivity is what drives the process to attach meaning to objective data. The validity of the interpretation of the results was furthermore confirmed by the peer-review preceding publication of Ref. #6.

C. Findings related to the propositions

In terms of the propositions, these are the main findings:

For proposition 7: to perform well in a complex design challenge, the (business) environment has to allow a high level of unpredictability of the outcome.

- The experiment with switching the level of novelty between contents and methods seemed to have turned out well enough. The explicit focus on visualisation and using different perspectives seems to have helps the acceptance of this new set-up. Still, both for the lecturers as well as the students the outcomes were far from certain in terms of the quality of the results. The mix of using supposedly strong design-skills (visualisation) to known contents while using new approaches and tools seems to have been experienced positively in this case.

For proposition 8: willingness by design engineers to embrace complexity implies not demanding or needing detailed instructions.

- The main dominant overarching pattern from the survey results is that this cohort of students in majority dared to take on the suggestion of using an unknown method even while feeling not well instructed. Taking on the new approaches and tools despite that feeling increased their understanding of their use and value, enjoyment and likelihood of future use. This result might be an indication on the preferable didactics with regards to new methods, i.e. allow freedom of choice and encourage trying out new things instead of explaining top-down in detail how to execute assignments and which tools to use.

For proposition 9: willingness to embrace external complexity is influenced by fear of internal complexity, i.e. the process resulting in a complex high-tech product.

- If, like in this course, the outcome of a design process or analysis is relatively known, the willingness of even junior designers to take on methods that face complexity head-on instead of shying away from it seems to be there. If the outcome is fully unknown, then the choice for approaches and tools that add to the complexity might for short assignments imply too much novelty. This is an assumption that would need further work to test.

Case #7, Alignment with management & funding, Deep (External)

As mentioned, the information that can be provided for case #7 is limited but because it is one of the available cases that touches management propositions most explicitly and could benefit from 1 on 1 (albeit NDA-restricted) dialogue with a company, its inclusion is justified.

Parts A and B are shorter than for other cases because the details of the case itself – like the product, the company, the geography, the exact stakeholders, the timing and so on – cannot be disclosed because these details are covered by an NDA. Nevertheless the core of the available information is described in amongst others Ref #8 and below in part A and B. By far the most relevant part is C, the findings with regards to the propositions that this case contributes to the overall picture.

A: Description of the case (contents)

This case was external, so the only one in the long list that did not involve students. The relevance of the case has however been indicated above and is touched upon in part B below. The text below serves as the case description and is taken directly from publication Ref #8.

> **SMART *is not always* Wise**
>
> *In a project that had gone through successful pilot-testing in an initial market (country), external funding was obtained to scale production, and sales targets were set for year 1. To facilitate scaling, budget was included to explore a second market.*
>
> *During that exploration, it was discovered that there might be demand for the product in the second market if it would be offered with a leasing option. This would require changes to the business model and product design. Since funding was obtained based on "SMART" targets there was only a direct incentive to sell a number of units of the initial product within the given period, in the initial market. Hesitant*

customers in that market when asked revealed that a leasing option would have been appealing if not preferred. The funding arrangement did however not encourage the company to offer that option.

Effectively, using "SMART" targets complicated entering the second market and reduced uptake in the first one, because of an in hindsight poorly informed and rigid solution. A more flexible approach would have worked with strategic intent ("How to address this multiform problem") and refrained from setting specific targets until better insight was created in the system, i.e., multiple diverse contexts. Instead the agreement was based on limited, possibly accidental, success on a small scale.

In the context of global sustainability, using simple overarching metrics may be counter-productive anyway. While likely intended to provide clarity, too specific overarching metrics can easily result in a yardstick that does not match the diversity of local manifestations. Catering to a large diversity of beneficiaries is also a sign of inclusiveness. This matters in the context of sustainability since inclusiveness is explicitly stated in five Sustainable Development Goals and implicitly in six more (Assembly, 2014).

B: Relevance for this thesis and research questions

The researcher engaged in several conversations with three employees of the company. The discussions started with explaining the CVD mindset and then exploring how it might (have been) relevant for one or more of their own cases. The case as described in part A above was the one that jumped out most explicitly. While interested in this way of working, their influence on their funders was not deemed sufficient for now to change course. Because of the relatively negative conclusion with regards to the way how the project evolved, the details of the case were asked to be omitted, in compliance with the NDA. Despite this, the case does provide relevant insights with regards to management aspects and propositions, and interplay between management (control) and design. In terms of the balance between design result and management considerations, this case tilted much more towards the latter which is why it adds value to include it in this thesis.

C. Findings related to the propositions

In terms of the propositions, these are the main findings:

For proposition 5: design outcomes following a CVD-approach potentially have a higher performance

- If "performance" is interpreted in terms of "quality" but defined as fitness-for-*multiple*-use   responsible managers might more easily recognise if a design result contributes to a wider sense of achievement than if performance is limited to fitness-for-use for one specific case.
- A problem with defining performance in terms of one use case is its immediate magnet-like working in terms of optimisation of the product, business model, value chain for that case. This may or may not work out on the short term, but may not be helpful for the longer term if that product is a smaller part of a more diverse portfolio.

For proposition 6: multi-contextual design spaces are likely to result in (more) inclusive results

- If "inclusiveness" is an explicit management consideration and accountability-area, managers may be more open to trying out a multi-context approach. That openness might again be hampered if they are only responsible for a small contextual area, e.g. geographically, with limited diversity.
- Inclusiveness might therefore have to be a metric on company level as a whole in order to encourage more holistic thinking in this regard.

For proposition 7: to perform well in a complex design challenge, the (business) environment has to allow a high level of unpredictability of the outcome

- Accepting a level of unpredictability can be encouraged by regular exchanges between contextually responsible managers to learn appreciate how "unpredictable" does not have to be "scary", and to learn how to adapt fluently rather than react rigidly.
- A level of "orchestrated collaboration" between managers, divisions, regions is likely to reduce the paralysing part of the feeling of unpredictability: once immediately feeling part of a larger collectve intelligence, it may be seen as - scary but not paralysing - reality.
- Only if a design attitude of adaptiveness is met by a similar management attitude in terms can designers and managers start to develop adaptive strategies. In all other combinations confusion, mismatches and lack of synergy are the result. If both attitudes are control-oriented that will only work in controlled and fully predictable environments.

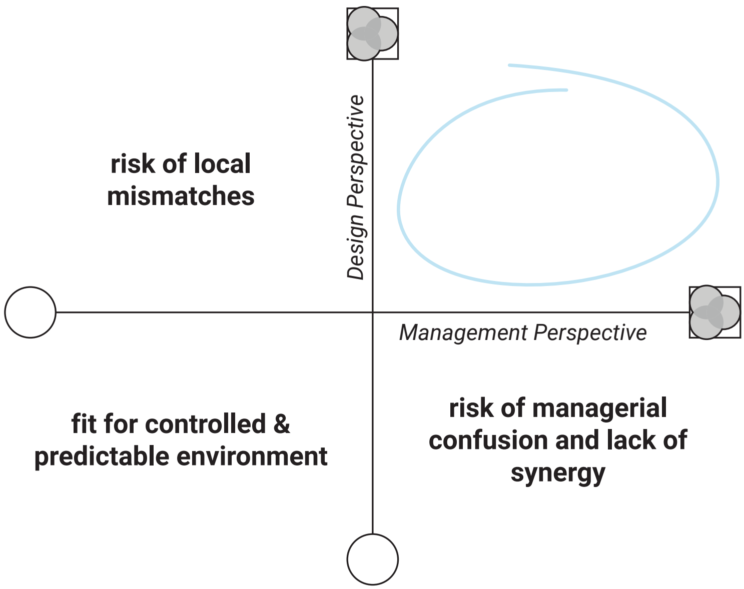


Figure A4.2 Combinations of design and management attitudes (taken from Ref. #8)

For proposition 9: willingness to embrace external complexity is influenced by fear of internal complexity, i.e. the process resulting in a complex high-tech product.

- If managers in the same company from different contexts (use-cases) meet and discuss their different perspectives and manifestations of the same reality more regularly, they may have less fear for what for them individually is unknown and complex, but start to recognise these characteristics as their shared reality [See Ref. #8]. This might easier bring them towards accepting the complexity of real-life challenges versus trying to fear it as something undesirable.
- When such intra-contextual social connections are a regular feat, the chance is very present that more connections between the contexts become visible in a positive way, i.e., as source for new ideas instead as source of fear.

For proposition 10: if decision makers think in terms of time-to-markets, they may allow a higher initial effort to include a wider diversity of requirements

- Time-to-proven-concept and time-to-first-market are hardly scrutinised as metrics, and funders of (development) projects may in fact encourage this themselves. Against the backdrop of scaling, it has to be questioned what a small-scale, mono-case, early-stage success can tell about a large-scale, diverse, full-stage situation.
- It seems more than just conceivable that if managers would consider time-to-markets as metric instead of time-to-proven-concept and time-to-first-market, their decision process in early stages would be less focused on quick success. One way how this might be achieved is to construct a company-wide metric out of the ones of (geographical) subsidiaries.

Appendix A4.4 Additional data case #2 (gasifier cook stove)

To be able to appreciate and understand the statements made in A4.3, case #2 particularly with regards to proposition 3, it is necessary to have access to the source data, i.e. the assessment scores of three assessors with regards to the three aspects that together made up the multi-level construct of “richness”. The three assessors for whom the scores below can be found are the Design team, as one, DE1 (Detached expert 1) and DE2 (Detached expert 2). For each assessor the scores are shown for three sets of insights (Rural, Urban and Shared). With regards to providing ‘objective’, or rather, unbiassed, scores, the Design team assessed their own insights so there was no reason to score any of them higher or lower than they actually judged them. The detached experts were presented with a full list of all insights, in random order and were not informed about the multi-context aspect so as far as they were concerned they had to provide their assessment for a large list of similar assessment-units (single insights). Their results were clustered back in the right set afterwards by the researcher. All further details on the assessment process and the analysis of the results are planned to be published.

All richness scores of all assessors are shown in the overview below.

Richness Scores by the design team

Rural Insights														
Basis for score	**#**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		**Total**	**Avg**
Representing multiple views		2	3	2	1	3	4	4	3	5	3		30	3.0
Be generative (open dialogue iso closing it)		4	2	4	2	4	4	5	3	4	4		36	3.6
Refer to connections between elements		4	3	2	1	3	3	2	1	1	2		22	2.2
Total		10	8	8	4	10	11	11	7	10	9		88	8.8
Average (Avg)		3.3	2.7	2.7	1.3	3.3	3.7	3.7	2.3	3.3	3			2.9
Delta Range		2	1	2	1	1	1	3	2	4	2			1.9
Urban insights														
Basis for score	**#**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		**Total**	**Avg**
Representing multiple views		2	4	3	5	2	5	2	5	3	3		34	3.4

Be generative (open dialogue iso closing it)		5	4	3	4	3	4	3	5	4	4		39	3.9
Refer to connections between elements		3	4	2	2	1	2	1	2	2	2		21	2.1
Total		10	12	8	11	6	11	6	12	9	9		94	9.4
Average (Avg)		3.3	4.0	2.7	3.7	2.0	3.7	2.0	4.0	3.0	3.0			3.1
Delta Range		3	0	1	3	2	3	2	3	2	2			2.1
Shared insights														
Basis for score	**#**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**	**Avg**
Representing multiple views		4	5	4	4	4	4	4	4	4	2	2	41	3.7
Be generative (open dialogue iso closing it)		3	4	3	4	5	3	4	5	5	5	3	44	4.0
Refer to connections between elements		4	4	2	2	4	2	3	5	5	3	2	36	3.3
Total		11	13	9	10	13	9	11	14	14	10	7	121	11.0
Average (Avg)		3.7	4.3	3.0	3.3	4.3	3.0	3.7	4.7	4.7	3.3	2.3		3.7
Delta Range		1	1	2	2	1	2	1	1	1	3	1		1.5

Richness Scores by detached Design Expert 1 (DE1)

Rural Insights													
Basis for score	**#**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		**Total**	**Avg**
Representing multiple views		1	4	1	1	3	2	3	2	2	4		23	2.3
Be generative (open dialogue iso closing it)		3	4	3	1	2	1	3	1	1	3		22	2.2
Refer to connections between elements		3	3	1	1	4	3	4	1	2	3		25	2.5
Total		7	11	5	3	9	6	10	4	5	10		70	7.0
Average (Avg)		2.3	3.7	2.7	1.0	3.0	2.0	3.3	1.3	1.7	3.3			2.3
Delta Range		2	1	2	0	2	2	1	1	1	1			1.3
Urban insights														
Basis for score	**#**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		**Total**	**Avg**
Representing multiple views		3	3	1	1	1	1	1	2	1	1		15	1.5
Be generative (open dialogue iso closing it)		4	5	1	3	1	1	1	3	1	1		21	2.1
Refer to connections between elements		3	3	1	1	5	1	1	2	1	1		19	1.8
Total		10	11	3	5	7	3	3	7	3	3		55	5.5
Average (Avg)		3.3	3.7	1.0	1.7	2.3	1.0	1.0	2.3	1.0	1.0			1.8
Delta Range		1	2	0	2	4	0	0	1	0	0			1.0
Shared insights														
Basis for score	**#**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**	**Avg**
Representing multiple views		2	2	3	4	1	2	3	5	4	2	5	33	3.0
Be generative (open dialogue iso closing it)		4	4	5	4	1	2	5	5	4	5	5	44	4.4
Refer to connections between elements		2	1	4	2	3	4	4	5	4	1	3	33	3.3
Total		8	7	12	10	5	8	12	15	12	8	13	110	10.0
Average (Avg)		2.7	2.3	4.0	3.3	1.7	2.7	4.0	5.0	4.0	2.7	4.3		3.3
Delta Range		2	3	2	2	2	2	2	0	0	4	2		1.9

Richness Scores by detached Design Expert 2 (DE2)

Rural Insights														
Basis for score	**#**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		**Total**	**Avg**
Representing multiple views		2	2	1	1	2	1	4	1	1	2		17	1.7
Be generative (open dialogue iso closing it)		4	5	4	1	4	5	5	1	1	3		33	3.3
Refer to connections between elements		2	3	2	1	4	2	3	1	2	2		22	2.2
Total		8	10	7	3	10	8	12	3	4	7		72	7.2
Average (Avg)		2.7	3.3	2.3	1.0	3.3	2.7	4.0	1.0	1.3	2.3			2.4
Delta Range		2	3	3	0	2	4	2	0	1	1			1.8
Urban insights														
Basis for score	**#**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		**Total**	**Avg**
Representing multiple views		1	1	1	1	1	1	1	2	1	1		11	1.1
Be generative (open dialogue iso closing it)		2	3	3	4	3	1	3	4	1	3		27	2.7
Refer to connections between elements		4	2	2	2	3	1	4	3	3	3		27	2.7
Total		7	6	6	7	7	3	8	9	5	7		65	6.5
Average (Avg)		2.3	2.0	2.0	2.3	2.3	1.0	2.7	3.0	1.7	2.3			2.2
Delta Range		3	2	2	3	2	0	3	2	2	2			2.1
Shared insights														
Basis for score	**#**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**	**Avg**
Representing multiple views		1	1	1	4	1	1	1	5	1	5	2	23	2.1
Be generative (open dialogue iso closing it)		3	3	1	3	5	1	3	4	4	4	4	35	3.2
Refer to connections between elements		3	2	1	1	3	5	3	4	2	3	3	30	2.7
Total		7	6	3	8	9	7	7	13	7	12	9	88	8.0
Average (Avg)		2.3	2.0	1.0	2.7	3.0	2.3	2.3	4.3	2.3	4.0	3.0		2.7
Delta Range		2	2	0	3	4	4	2	1	3	2	2		2.3

Appendix A4.5 Additional data case #5 (graduation evaluation)

This Appendix contains the replies to the open questions of the five graduation students who were asked to complete an evaluation. These replies have been triangulated with the responses to the closed questions to serve as input for part C of the case in section 4.2.2.

The students (S1 – S5) were given two open questions that gave them the possibility to elaborate both on process and contents, and imagine what the influence of CVD was on both, if any. They had full freedom, and were invited as such, to mention both negative as well as positive experiences, which is indeed what happened, judged by the results.

1. ***Results*** *Reflect on the likely differences between the current outcome compared with what you – to the best of your assessment – would have come up with without CVD? What are the most noteworthy differences, if any, and how do you value the differences (positive or negative)*

S1:

Theoretical – more difficult to choose a focus

On the one hand my results became a bit more theoretical than planned. Yet this also shows that it is very well grounded and inclusive. This approach makes it even more difficult to choose a focus since there are so many interesting and inspiring insights gained that I was tempted to try to fit all in my final design.

Clear influences from all contexts, and results during the whole process

The results are clearly not the same from if I would have used another approach, or at least wouldn't focus on more than one context. My final products are the result of insights from all contexts, and for example the target-group wouldn't have been discovered if I didn't go to all contexts.

More broad and complete view on the topic

All the research results give me a better way to be critic on current papers written on this subject (the acceptation of insects as ingredients). After doing research in all contexts, it somewhat gives me the feeling that I generated more information than others that wrote about it; that my view is more complete.

S2

With a number of design choices (see below) as examples: if I only would have based by design on one country, the choices would certainly have been different. The design became much stronger/ robust/ adaptable because I did not focus on one country.

Design choices included:

- *Required power range in Watts (260-425 vs 320-660)*
- *Shape of pans: in Ghana they use round bottomed pans; if only focus on Uganda this would not have been taken into account*
- *Location of pans: the pans should not be in direct contact with the charcoal for the technology to work properly. In Ghana people would have to be notified of that, in Uganda it turned out to be am extra benefit because of fear of blackening the pans*
- *In Ghana affordability of gas as fuel is seasonal (in wet season), in Uganda some dishes simply are better prepared by using gas.*

S3

The CVD mindset helped to consciously generate ideas by making mono-contextual insights interact. More importantly these ideas seemed to lead to inclusive and scalable concepts. The ingredients were on the one hand coming from a broader search and more holistic, on the other hand they were mostly less deep and precise.

CVD forced me to obtain insights from more perspectives than I would have done otherwise. This also encouraged me to borrow from my own experiences in one of the countries, but not as end point, also to dig deeper in the other context. Personal experiences can help but you don't always realise their relevance. They can also create bias however.

S4

Some insights were a bit shallow, it was difficult to get insights on the same depth especially if you do not go to a context itself.

Somehow CVD provides more direction where to source inspiration.

On strategy level the results are more adaptable, on product level less certain of that

Without CVD I would have focused more on one context (Sint Maarten). Looking back I realize that the business case would not have been viable there because they do not have the same resources as here. That would have caused me to get stuck. On the other hand, I also think here in NL we do not have all the resources. With CVD I could create an overview of opportunities on how the markets/ products/ activities/ can be combined or how they can contribute to each other.

S5:

In terms of the outcome of results, I feel there likely is a large difference between the CVD process and the more "regular" Double diamond model. Since the more narrow start in a double diamond model there is probably less wiggle room so idea directions and concepts end up much more similar to each other than in the broader CVD process. During this project a switch needed to be made since the chosen idea direction turned out to have a hurdle too big to overcome, thus no longer being feasible. A very different direction was available to make a quick switch and evade this hurdle. In the double diamond model this might have resulted in scrapping all concepts and ending up without a foreseeable solution. Resulting in having to start analysing once more and losing a lot more time. In the context of a fixed time project like a graduation project, this might not only have affected the result itself but also its quality, or even the entire planning. Resulting in a delay for finishing the project.

Furthermore I think the result is accounting for more types of use than a different approach would have done. The end result therefore feels more versatile and more inclusive. Although the final result was optimised for four different types of use groups, using satisficing methods, thus resulting in a single implementation variant. The requirements for all use groups are still recorded, as well as the decisions made to cater to these requirements. It is thus a quick process to switch from the combined implementation variant to multiple use group specific implementation variants. In a double diamond process there would likely be only one use group to cater to, making the final result a lot narrower in its application. I therefore feel the end result is able to reach out to more people and has a better place in the market of application. In simple terms I feel the end result is better than I would have been able to create following a different approach like the double diamond.

2. ***Process*** *What does the CVD-approach and mindset add to your arsenal as a designer, where does it complement, build on, expand existing approaches or methods? If it adds or complements nothing, which approaches (e.g. from the Delft Design Guide) do you consider to cover your needs?*

S1:

More open and broad mind-set

CVD made me start more open and broad, and do unfocussed research to get a broad solution space. It resulted in that I was more explorative into different directions, and found more inspiration from directions I didn't expect.

Limiting familiar methods & approaches

On the other hand, most of the previous taught methods & approaches are focussed on familiar contexts, thus an approach that involves more contexts also means that all other methods and processes known, needs tweaking to fit all contexts. It confused me a bit, because it is already quite vague what information is needed with a less specific problem. So what research and design methods & approaches to use, was now not only based on the subject, but also on the broadness of the CVD, and also on the different (new) contexts.

S2

I have not found any other approaches that so explicitly emphasise involving stakeholders and users from different countries. This approach demands of the designer to make use of other methods as well (i.e. it is not exclusive but encourages method-inclusiveness). In combination with the Opportunity Detection kit, CVD was very useful. It is sort of an overarching method that gives direction to using other more detailed methods.

S3

CVD was very helpful in the process. This mindset is also present in some other methods for example if insights from various scenarios are imagined. However, the interactions between these different insights are not carefully studied whereas with CVD you focus on analysing these very interactions.

The majority of time in my assignment was spent on doing the research as opposed to designing etc. This was in part due to having to deal with a moving target. New ideas generated new questions and so on. With an explorative research it does make sense to start out not with too narrow questions but it is difficult to control and make sense of the overwhelming number of insights.

Especially in these circumstances it is important to decide when to stop researching, One tip that could help is to make working towards a more specific set of detailed research questions a goal. To reduce the risk of too much bias it would be good to actively engage with people from other disciplines when working with the mono-context insights to create shared insights. I would also like to go back to defining the problem phase while utilising CVD approach during the initial research.

One key lesson that I learnt is the difference between explorative, more holistic research and more specifically directed reductionist research. In my case it was more, and probably too much of the former, and too little of the latter. I believe the CVD approach in an analytical setting can be more relevant and helpful compared to explorative settings.

S4

Because of rethinking and rewriting the process can feel inefficient.

Focusing on multiple (geographical) contexts makes sense when working development of natural materials in order not to mess up local nutrient cycles. It can also be of help in materials design because I could link context insights with material characteristics and development. They were very logical to combine, using present and future opportunities and threats-tool.

It was helpful and meaningful in creating a narrating approach as well because I noticed that storytelling to many stakeholders became quite complicated; stakeholders expand quickly when combining contexts. For this I used an audience map to create an overview of audience interests.

I used the CVD mentality of embracing complexity to be able to address certain clashes of value between stakeholders for the development strategy of the material. Within this strategy I allowed the material to have different levels of complexity and communicate those in the strategy, designed for multiple applications so that industries can more easily find common ground with a material to start with a transition to a bio-material. Also I based my strategy on availability of resources, that are made available through combining contexts. *Parallel local relevance combined with multi-context viability can bring about decisive acceleration of a transition.*

S5

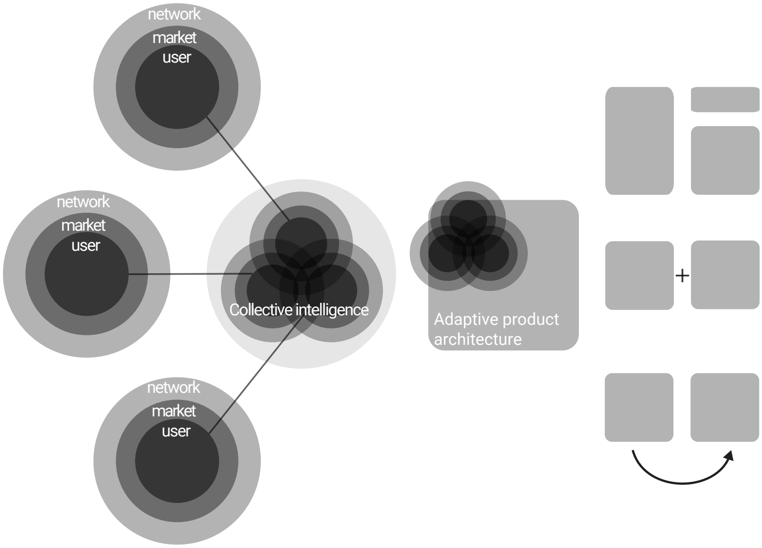
The CVD approach combines my desire to keep a broad view, whilst still finding enough depth and details when necessary. It is open enough to allow a designer to select the correct tools for each subset, without getting too vague, whilst still being guiding enough to keep a strict view on processes and steps to come, thus not getting lost. It offers a strong backbone to start designing from.

The approach really satisfies my desire to look beyond a single persona or target audience. The approach of combining multiple different types of use allows for different opinions within a single use group as well. Since for a chosen application use groups tend to have enough overlap, or similarities, to account for all kind of hybrid users, in between the more fixed settings of the single use groups, who would otherwise have been (partially) left out. Hence the feeling of a more inclusive result.

Challenging for me was the scale of the contexts. Since rather than starting with a problem, a material that needed an application was the starting point. Therefore all contexts, that one could think of, were available. The chosen contexts therefore ended up too broad, and the insights probably too generic. It would likely have been better to take one of these very broad contexts and take it as a starting point, with its multiple different smaller contexts as varied starting contexts. Combining the insights from the broader contexts was therefore difficult and went almost automatic the second time round, with the different types of use for the final design direction, which was done instinctively, without a dedicated session.

In this project the decision was made to start with contexts that were selling markets for the company, but this easily could have been different. A proper way to select the first contexts however was difficult and might even have required some research in and off itself beforehand. For instance multiple steps working from broad contexts, discovering the smaller contexts within, to then analyse and combine the smaller contexts of the most promising broader area. This slightly happened during this project already, by ultimately discarding, or rather not continuing on one of the larger contexts and keep looking for different types of use, within the other context. As described above.

The method of aiming to get specific insights out of the contexts helped structure the information found and resulted in a clear goal to work to when implementing an analysis step. The next step of then combining these insights also helped in making sure all information found was actually used in following steps, rather than working with a tool to a conclusion and leaving it at that. This clear structure allowed me to feel in control of the project much better than I have felt before. It allowed me to keep control and not get overwhelmed by the project.



The visualisation of the approach also clearly shows the inherent diverging and converging moments. The different contexts analyses allow for a broad analysis, diverging, whilst the focus on finding clear and concise insights are converging moments within those contexts. Combining them converges more, but also reverges, or clusters, finding those combined insights and allowing for reflection during the process. The next step is the ideation, which is not clearly shown as another diverging stage, that converges back to the product architecture, which again allows for diverging into different implementation variants, which again can be converged for the chosen variants once more. By having these steps somewhat linked to a specific moment in the approach it becomes easier to go to the next step. When analysing the contexts, for instance, the knowledge gained translates to insights, which already start interacting in the back of the head, almost leading themselves to a combination session as more insights are discovered. In a similar way the idea of multiple implementation variants encouraged me to find the different types of use, and find similarities and differences for them.

Appendix A4.6 Details of accepted publications

The list below shows the details of the externally peer-reviewed accepted publications by the researcher that address one or more (elements of) cases and case studies that are mentioned in this thesis. Not all publications are fully open access, but all can be made available on request.

1. Kersten, W.C., Diehl, J., Crul, M.R.M., van Engelen, J.M.L. 2016 A *multi-context design approach for a maternal health care product* (conference paper, Norddesign 2016, 10-12 August, Trondheim, Proceedings Vol. 1, pp. 258-267).
2. Kersten, W.C., Diehl, J, Crul, M.R.M. 2017. *Influence of context variation on quality of solutions: experiences with gasifier stoves* (presented at Global Conference on Sustainable Manufacturing 14, 2016, 3-5 October, Stellenbosch; published in Procedia Manufacturing, Vol. 8, pp. 487-494
3. Kersten, W.C., Long, N.H., Diehl, J., Crul, M.R.M., van Engelen, J.M.L. 2017. *Comparing performance of biomass gasifier stoves: influence of a multi-context approach.* Published in: Sustainability, Vol 9 (issue 7), p. 1140-
4. Kersten, W.C., Diehl, J., van Engelen, J.M.L. 2018. *Putting the horse in front of the wagon. How a multi-contextual design space successfully addresses complex challenges.* Presentation and working paper in Proceedings of RSD6, October 2017, Oslo, Norway.
5. Diehl, J., van Sprang, S., Alexander, J., Kersten, W.C. 2018. A *scalable clean cooking stove matching the cooking habits of Ghana and Uganda.* Presented at IEEE GHTC 2018, San Jose (US), 18-21 October 2018, published in Proceedings.
6. Kersten, W.C., Diehl, J., van Engelen, J.M.L. 2018. *Facing complexity through varying clarification of the design task.* Published in: FormAkademisk Vol. 11, issue 4, Article 2, page 1-28
7. Kersten, W.C., Diehl, J., van Engelen, J.M.L. 2018b. *Using a multi-context design approach as manifestation of complexity: perceptions and experiences of students in design engineering.* Published in: Journal of Design Research. Vol. 16, issue 3-4, pp. 214-246.
8. Kersten, W.C., Diehl, J., van Engelen, J.M.L. 2019. *Intentional design for diversity as pathway to scalable sustainability impact.* Chapter 16 in: Innovation in Sustainability, Bocken et al, Palgrave, pp. 201-309.
9. Kersten, W.C., Diehl, J.C. van Engelen, J.M.L. 2019. *Making frugal innovations more inclusive by embracing complexity.* Working paper, version 1. Delft. Available online

Additionally, a small number of publications has a connection to this research but they have not been extensively independently peer-reviewed so are not counted as formal academic publications.

10. Context Variation by Design, Working paper v4.0, Kersten et al (2015), available via web-site
11. CFIA Paper on inclusiveness (Kersten and Diehl, 2015, light external review)

Contents of the research has been presented in academic and non-academic settings at events in China, Mexico, the Netherlands, Norway, South Africa, UK, USA.

Appendix A6.1: Abstract CVD 2.0

*Words or sections marked with an * signify the most important changes with (presenting) CVD 1.0. Words printed underlined signify the key notions of CVD 2.0 (some of which the same as 1.0)*

CVD (Context Variation by Design) is a product/service development approach that has as a starting point that the complexity of contemporary society should be acknowledged and worked *with* to achieve better results. More often than not, a design task is (over)simplified to make it 'manageable'. In particular the focus is often on one context in order to respect the micro specifics of that context. This is tempting and seems sensible. However by severing the ties of the narrow scope of the design task with the rest of reality, such an approach is increasingly likely to result in design outcomes that do not match requirements from other contexts. This complicates or blocks and thus the ambition to achieve large scale impact. CVD *intentionally* acknowledges real-life complexity early on to enable large-scale impact to be achievable with lower overall resources (time and money).

As has become apparent, an important factor in creating the right conditions is to align the expectations on the expected benefits as early as possible in a way that resonates* both with the priorities and preferences of designers and managers who need to approve the approach.

The main outline of a CVD-driven process:

- **Reality is complex, problems are multiform:** Be open about the reality that problems are not isolated to a singular context. Most problems occur in different contexts simultaneously, but in different ways. This implies that different perspectives are required if one aims to address this problem in these different contexts. This so-called multiformity of such a problem therefore needs to be captured as early as possible by means of early variation of contexts and information therein. This results in a multiform design brief* that pays more attention to the differences in the key dimensions* of the problem (e.g., affluence of user-groups, geophysical considerations) than the direct contexts (e.g., country X and Y) themselves. The design brief outlines the multiform design task from which the full list of requirements is derived.
- **Empirical research and insights**. Each of the contexts that is chosen based on their combination of key dimensions needs to be investigated. This can be done by the same designers, or in parallel teams. Some coordination is desirable, the main requirement is

that the depth of information they obtain is of a similar level*. The information should be condensed in a workable set (10-20) of insights per context, so-called mono-context insights.

- **Rich design space**. The mono-context insights are then considered jointly in a rich design space. Here designers can use any design tools they consider appropriate*. There is no fundamental difference with a regular design process, the information just comes from more diverse contextual sources, which are all equally important. This prevents that design concepts that are constructed based on these insights are optimised for one context. Several concepts can be devised and eventually a tentative integrated adaptive architecture is proposed. The architecture set-up is likely to contain generic elements, but also modular (in/out) or flexible (adjustable) and context-specific ones. Some of the design choices are likely to not be thought of easily when working from a set of mono-context insights. As it turns out in practice, combining requirements does not automatically lead to compromises but invokes a higher level of latent functional creativity*. The proposed architecture is checked against the full list of requirements before it is finalised, including the sub-set that will be implemented first (X1). This architecture itself is 'robust'* towards multiple contexts.
- **The main benefits**: the direct results of this approach are 1) combining information from contextually diverse sources, 2) in a rich design space, 3) to enable construction of an adaptive architecture, 4) that allows expansion to multiple contexts without expensive redesign and delays.

CVD-design characteristics

The CVD-approach has four main characteristics that work together.

- Systematic Variation: apart from the more regular variation within the design task, already vary the contextual perspectives before the design task is set in the first place, to arrive at a multiform design brief*.
- Hierarchical decomposition: instead of dividing the larger problem in sub-problems and sub-systems (e.g. countries) to be tackled separately, determine the key dimensions* so the problem is formulated in terms of these dimensions.
- Satisficing: when constructing the adaptive architecture, do not focus on "optimising" (for one context), but ensure that the main requirements from each considered context are met sufficiently, and improve from there.

- Discursiveness: a design process should contain all necessary activities, but not necessarily in one given order. This starts with acknowledging the longer-term outlook, i.e., covering requirements from multiple contexts.

Practical considerations

The approach and associated mind-set* is not served by providing detailed instructions. Many existing tools and design methods are available to designers to choose from for the specific activities within the design process. Two main guidelines are provided, to address main concerns as they have arisen in practice*:

- There is no absolute number for the number of contexts to include. The minimum number is of course two, and if relevant three or four. Relevance* is determined by a sufficient degree of differences between the contexts, while still having touch points.
- Designers like to think in terms of divergence – revergence* – convergence. When using the CVD-approach, the different sets of insights within the design task represent this flow, respectively: sets of mono-context insights – rich design space – set of shared insights.

Alignment between* design and management considerations and expectations

As has become apparent* in many instances, to reap the full rewards of a CVD-approach, early alignment between* design and management considerations is required. The approach is likely to require a higher use of (personnel) resources at the start, with good reason. This results in the following recommendations:

- To align the 'language' of designers and managers, the design task should also* be expressed in a more general form, e.g., a Project Initiation Document*.
- It should be emphasised that the resources spent on a broader – multi-contextual – approach at the start result in high-quality* information when this quality is still relatively inexpensive* to achieve. Increasing quality once production and distribution investments have been made is more expensive.
- The multiform approach and design task require a diverse team* from the start, also within the design stage.
- While the predictability and uncertainty of the outcome of the design process may seem higher, once that outcome (the adaptive architecture) is there, the uncertainty about the actual *scalability*

*potential**, from the product/service point of view is much lower. Actual success in multiple contexts then depends on the broader management capabilities.

- To support a longer-term multi-contextual design strategy, management accountability metrics need to be in line with this, e.g., expected time-to-markets*.

Appendix A6.2: Applying CVD-thinking outside the product design domain

CVD was conceived with the design engineering domain as application area with products and services as main intended design outcomes. As has become apparent in conversations with professionals outside the design engineering domain that it I not difficult to see how the main principles and outcomes of the CVD-approach as presented in this thesis might apply as well to any situation that refers to a large-scale problem and a 'non-product centred' solution direction that requires eventual scaling.

To briefly demonstrate this, this Appendix applies one of the outcomes of this thesis to a project that did not have a product or service as outcome but did explicitly aim for scalability and inclusiveness of lessons taken from a range of pilots. The Appendix briefly demonstrates how applying the *three-layer adaptive architecture* model that was briefly discussed in section 5.3 might enhance these results even more in terms of usability.

Description

"Improving anticipation and social inclusion in Living Labs for Smart City Governance"

Smarter Labs – Urban Europe Joint Programming Initiative (2016-2019). http://www.smarterlabs.eu

The results were published in a synthesis report (Dijk et al., 2019) and tentative academic reflections published in (Dijk et al., 2018).

The SmarterLabs project aimed to develop a Smart City Living Lab approach to effectively deal with two major risks to successful, widespread implementation of smart transport technologies. These two risks concern (1) unforeseen barriers to large-scale change in socio-technical systems, and (2) exclusion of social groups not matching the required 'smart citizen' profile. Based on action research in Living Lab experiments in the cities of Bellinzona, Brussels, Graz and Maastricht.

Some key outcomes

Below some of the key outcomes of the project as taken from the synthesis report (Dijk et al., 2019):

- Lessons were identified with regards to constraints to social inclusion from and within labs, and constraints related to general design and contextual specific with regards to scaling the experiments.

- The micro-practices of the Living Lab need to be strategically designed and then jointly orchestrated
- No immediate replication of Living Lab examples of best practices is likely to be successful if it is not adequately customised and adapted to changing conditions in the outside social and political agenda.
- Efforts to connect the Living Lab with the broader societal developments need to be done while designing the Living Lab and throughout its development. This requires a degree of flexibility and adaptability to changing external conditions, involving – when needed – adjustments and re-framing.
- In particular, what can reasonably be scaled up should be identified since the very beginning of Living Lab activities and an upscaling strategy should be designed

Link with intentional 'Design for Scalability & Diversity'

To capitalise in the best way on the collection of findings, the three-layered adaptive architecture model that was introduced in this thesis is now applied to determine whether it can provide a structured basis for next efforts. If so, it can better enable future Living Lab designers to design their efforts to be inherently scalable, in size and/or replication potential. The scaling potential does not merely refer to making a small lab bigger or replicating lessons from one lab to the other but instead distinguishes more precisely what parts are generic, which components are mostly present in any lab but in different shapes, forms and combinations, and which elements are context-specific.

The adaptive architecture for the outcome of this project might look as follows:

Generic (and joint) principles:

- Consider the local eco-system (context) when designing the Lab in detail, e.g. in terms of goals, relationships with institutions, inclusion dynamics, conflicting goals.
- While the extent and way may vary it seems advisable to always work constructively with the municipality.
- Capitalise on existing trust relationships within communities.
- Consider diversity of (needs of) target groups from the start instead of making assumptions about preferences of different groups.
- Strongly consider to engage with people from different target groups before designing the lab and its activities to be able to obtain actually perceived reasons for interest as well as the opposite, reasons for not feeling spoken to. Better understanding these different reasons is important input for communication and detailed design of activities (using the adaptive and contextual layers). See side-bar.
- Establish a joint and freely accessible database of activities/ formats for Living Lab organisers for inspiration (not blueprinting).
- Citizens need to be at the core.
- Repeat stakeholder analyses regularly to spot changes in potential target groups. More in general, the execution within the lab should be subject to emerging new insights.

Adaptive components:

- Choose a theme that is locally relevant and perceived as priority.
- Targeted calls that resonate with specific target groups, based on pre-engagement with a diversity of groups (see third principle above).
- Use go-to-persons within communities.
- Use different times in the day and week to organise activities as recognition of the different life rhythms that people have.
- Use digital as well as analogue mediums.
- Realise that the window of opportunity for upscaling very much depends on contextual dynamics (politics, events, specific problems, ‘incidents’, priorities).

Context-specific elements:

- Sort of venue, language, style/ tone of voice, time schedules.

Using such an architecture seems to add value to the results as communicated through the synthesis report. Thereby it would enable learning (locally and between labs) and is recognisable without new Labs feeling as direct copies from each other. Thereby it would respond to the stated finding on the need to “design strategically and orchestrate jointly”.

Samenvatting

Samenvatting

Huidige situatie

Design engineers hebben een inherente motivatie om iets nieuws te creëren, meestal een product. Ze hebben ook graag de vrijheid om hun creativiteit tot bloei te laten komen om dat te bereiken. Ze moeten echter ook iets creëren dat relevant is voor de maatschappij en hun opdrachtgever, tenminste als hun doel is om een daadwerkelijk ervaren probleem te adresseren. Sinds WW1 heeft de opkomst van door industrialisatie gestimuleerd systematisch ontwerpen geholpen om betere, meer relevante resultaten te bereiken. Creatieve vrijheid wordt op die manier in enige mate gestructureerd om de kans op relevantie te vergroten.

Het standaard *design engineering* proces bestaat uit discursieve stappen en voortdurende verificatie van resultaten van iedere stap met het programma van eisen, wat kan leiden tot een aanpassing van die eisen. Alle stappen dragen bij aan de creativiteit ten behoeve van de maatschappelijke relevantie en een bevredigende ontwerp uitkomst.

De structuur waarin creativiteit tot uitdrukking komt kan verder worden verduidelijkt door de voornaamste karakteristieken van een design engineering proces te benadrukken: de ontwerptaak wordt afgeleid van de probleem definitie en bakent de ontwerpuitdaging af. Nadat de ontwerptaak is vastgesteld kan systematische variatie ten eerste worden toegepast om het probleem en dus de taak op te delen (decompositie) en later om een morfologische kaart te maken (ontwikkelen van deeloplossingen) en om verschillende combinaties uit te proberen om uit te komen op een aantal mogelijke geïntegreerde oplossingen. Tijdens dit proces wordt het resultaat van iedere stap aangehouden tegen het programma van eisen die voortkomen uit de ontwerptaak, wat kan resulteren in het aanpassen van de eisen. Stappen in het proces hebben niet een vaste volgorde (discursiviteit), waardoor de eisen voortdurend kunnen mee-evolueren. Bij het construeren van geïntegreerde oplossingen, bij het vergelijken met de eisen en bij het selecteren van de beste totaal-keuze is sprake van *satisficing*. De keuze voor de uiteindelijke oplossing is de optimale voor de afbakening zoals die was vastgesteld. Of die oplossing in lijn is met eisen buiten die afbakening is geen primair aandachtspunt.

Het probleem

Ontwerpuitdagingen worden steeds complexer, onder andere omdat de ervaren werkelijkheid steeds complexer wordt: (elementen in) de maatschappij zijn meer met elkaar verbonden dan voorheen en veel problemen manifesteren zich op verschillende en snel veranderende manieren, dat wil zeggen in verschillende contexten, die ook -vaak wederzijdse- afhankelijkheden hebben. Daar bovenop zijn er factoren waarmee in de praktijk interferentie is, die ontwerpers niet actief kunnen beïnvloeden, zoals (geo)politiek, structurele ongelijkheid en ad hoc crises. Dit alles doet zich bijvoorbeeld voor bij alle problemen die te maken hebben met duurzaamheid. Vanuit het perspectief van design engineering hebben de verschillende contexten een diversiteit aan eisen tot gevolg. Hoe kunnen *design engineers* omgaan met deze groeiende diversiteit en de waarschijnlijke wederzijdse afhankelijkheden tussen contexten?

Creativiteit bij voorbaat opofferen is niet iets waar de meeste ontwerpers open voor staan. Het antwoord wordt daarom meestal gezocht in het structuur-aspect. Een reguliere manier om met de complexiteit en het reduceren van de diversiteit om te gaan is door te simplificeren, dat wil zeggen door een specifieke context te kiezen als afbakening voor de ontwerptaak. Context kan worden beschouwd als een combinatie van omstandigheden die bij elkaar horen waarbinnen een specifieke manifestatie van een algemener probleem wordt ervaren. Veel voorkomende voorbeelden van contexten zijn landen of regio's of specifieke doelgroepen daarbinnen. Binnen de versimpelde ontwerptaak verwacht de ontwerper nog steeds in staat te zijn om creativiteit te gebruiken om een optimale oplossing te bereiken voor de gekozen afbakening van die ontwerptaak. Hoe met diversiteit van contexten om te gaan is van later zorg.

Wat we in de praktijk kunnen zien is dat deze manier van werken niet langer voldoet in een sterk geglobaliseerde en zich snel evoluerende maatschappij met dito problemen en veel onderlinge en wederzijdse afhankelijkheden. De initieel optimale oplossing bepaalt het pad voor de volgende stappen in het implementatie proces, dat wil zeggen dat die pad-afhankelijkheden creëert en lock-in voor implementatie buiten de initieel gekozen context. De moeite die dan nodig is om oplossingen te herontwerpen om te voldoen aan de eisen voor die nieuwe contexten beperken, vertragen of blokkeren zelfs het pad naar positieve impact op grote schaal. Vooral als die problemen gerelateerd zijn aan duurzaamheid of betrekking hebben op basiskwaliteit van leven is die schaal zeer groot, de onderlinge afhankelijkheden talrijk en de noodzaak om impact te creëren groot. Diverse projecten in het eerste decennium van deze eeuw, inclusief op deze faculteit, behandelden het probleem al dat hier wordt benoemd. Tot nu toe heeft dat geen grote wijzigingen in de alledaagse praktijk teweeg gebracht.

Onderzoeksfocus

Het is daarom de moeite waard om te onderzoeken welke (soorten) veranderingen wenselijk zijn voor *design engineering* om deze ontwikkelingen het hoofd te bieden. Zoals eerder aangegeven kan *design engineering* niet alle aspecten meenemen ten behoeve van bereiken van positieve grootschalige impact. Verdere evolutie van *design engineering* zou niettemin een relevante bijdrage hieraan kunnen leveren. De verandering, dat wil zeggen de volgende stap in deze evolutie, is het onderwerp van onderzoek in deze thesis. Dergelijke verandering moet tegelijkertijd een nieuw perspectief bieden en niet te nieuw zijn voor ontwerpers. Om die reden wordt het meest gebruikelijke *design engineering* proces als maatstaf genomen.

Daarom lijkt het gepast om de oudste ontwerp karakteristiek te gebruiken als startpunt: systematische variatie. Die karakteristiek werd voor het eerst toegepast door Leonardo da Vinci. De verandering waarop wordt gedoeld is om niet te wachten met deze karakteristiek tot nadat de ontwerptaak is vastgesteld, maar om het al eerder toe te passen door vanaf het begin meerdere contexten tegelijk mee te nemen.

De Hoofdonderzoeksvraag (HOV) voor dit proefschrift is daarom als volgt geformuleerd:

Welke inzichten en kennis, zowel vanuit de theorie als ondersteund door de praktijk, kunnen worden gegenereerd met betrekking tot een design engineering aanpak waarin systematische variatie van contexten wordt gebruikt voordat de ontwerptaak is vastgesteld teneinde, in het bijzonder, multi-contextuele complexe maatschappelijke vraagstukken te adresseren?

Om verdere focus aan te brengen en de nadruk voor dit onderzoek te verduidelijken, worden twee invalshoeken benoemd. Deze invalshoeken geven richting voor het afbakenen van het literatuur onderzoek en voor het structureren van de bevindingen, discussie, conclusies en aanbevelingen.

1. **Design engineering arsenaal**: wat mogen we op basis van onze kennis over het huidige arsenaal aan (systemische) ontwerpmethodes, -aanpakken en hulpmiddelen verwachten, dat een aanpak met een nadruk zoals geformuleerd in de HOV daaraan kan toevoegen? Om dit te kunnen beoordelen valt te verwachten dat een aantal gedefinieerde constructen nader moeten worden beschouwd. De keuze voor deze constructen is gebaseerd op eerste verkennend onderzoek en ze worden later in meer detail onderzocht.
   - Context: in dit onderzoek wordt onder **context** verstaan een combinatie van omstandigheden die bij elkaar hoort waarbinnen een specifieke manifestatie wordt ervaren van een generiek voorkomend probleem. Wat onderscheidt contexten van elkaar? Een logisch en gebruikelijk onderscheid wordt aangebracht door landsgrenzen te kiezen als afbakening. Afhankelijk van het soort probleem zijn echter ook andere soorten afbakening vermoedelijk relevant. Tegelijkertijd is het waarschijnlijk niet nodig om al te veel verschillende contexten mee te nemen. Hoe kunnen we dus de relevante contexten identificeren en selecteren?
   - Rijkheid van de ontwerpruimte: wanneer we de multi-contextuele realiteit toepassen op het vaststellen van de ontwerptaak, wordt de afbakening daarvan doelbewust ruimer dan gebruikelijk. Die extra ruimte kan ontmoedigend overkomen omdat die leidt tot een

grotere hoeveelheid informatie die de ontwerper in overweging moet nemen. Daarom is het belangrijk om te beseffen dat de doelbewuste diversiteit ervoor zorgt dat de informatie in de ontwerpruimte **rijk** is en daarmee waarschijnlijker de (wederzijdse) afhankelijkheden tussen de verschillende contexten laat zien. Om dit voldoende te waarderen moet het begrip rijkheid beter worden begrepen.

- Adaptieve product/ dienst architecturen: een oplossing die is geoptimaliseerd voor een specifieke context schiet tekort in het voldoen aan eisen die worden gesteld door een multi-contextuele realiteit. De wenselijke uitkomst van het ontwerpproces zou eerder de vorm moeten aannemen van een **adaptieve architectuur die robuust is t.o.v. verschillende eindgebruikersscenario's (contexten).** Dit houdt in dat de architectuur als basis dient voor versies die met ten hoogste minimale aanpassingen tegemoet komen aan eisen in verschillende contexten.

2. **Empirische aspecten:** in de faculteit en sectie waarin dit onderzoek is uitgevoerd zijn onderwerpen die vaak worden behandeld duurzaamheid(simpact) op grote schaal en inclusiviteit, die beide meestal een hoge mate van complexiteit impliceren. Dit zijn de onderwerpen waarop dit onderzoek zich richt. Een aanpalend veld dat haalbaar is om mee te nemen om de kans te vergroten dat een verandering in de *design engineering* aanpak in de praktijk kan bijdragen aan bereiken van impact op grote schaal, is 'management'. Deze thesis verkent daarom hoe de verandering in de aanpak voor product of dienst ontwikkeling in lijn kan worden gebracht met management overwegingen en besluitvorming om een lange termijn perspectief (implementatie in meerdere contexten) zeker te stellen. Bovendien moeten gezien de keuzes voor de focus van het empirische deel van dit onderzoek (zie sectie Onderzoeksaanpak) ook de implicaties voor design engineering onderwijs worden onderzocht.

Onderzoeksaanpak

Dit proefschrift betreft verkennend onderzoek. Derhalve is de onderzoekaanpak, die in detail in hoofdstuk 2 wordt beschreven, inductief. De scope zoals eerder aangegeven is nog steeds breed. Om het onderzoek concreter te maken wordt een *design engineering* aanpak voorgesteld om centraal te stellen als herkenbaar ankerpunt voor het onderzoek. Die aanpak draait om de voornaamste constructen zoals die hierboven uit de doeken zijn gedaan: 1) **systematische contextuele variatie** *voordat* de definitieve ontwerptaak is vastgesteld, 2) resulterend in een grotere mate van **rijkheid** in de ontwerpruimte, 3) die de ontwerper in staat stelt om een goed geïnformeerde *inherent* **adaptieve architectuur** te creëren als *uitkomst van het ontwerp proces* 4) die de mogelijkheid biedt om **grootschalige duurzaamheidsimpact** te bereiken. Deze aanpak heeft als naam Context

Variation by Design (CVD), wat staat voor doelbewuste variatie van contexten die recht doet aan de complexiteit van de ontwerpuitdaging. De keuze om deze aanpak centraal te stellen als herkenbaar ankerpunt betekent niet automatisch dat dit de enige of beste optie is om het beschreven probleem het hoofd te bieden.

De thema's voor het uitgebreide literatuuronderzoek (hoofdstuk 3) waren afgeleid van de twee voornaamste invalshoeken zoals die eerder zijn aangegeven, en zijn: *geschiedenis van design engineering*, *een geglobaliseerde maatschappij*, *bereiken van grootschalige duurzaamheidsimpact* en *omgaan met complexiteit*. In lijn met het inductieve proces zijn de resultaten van het uitgebreide literatuuronderzoek – op een iteratieve manier en na uitvoerige discussie met ontwerp experts – samengevoegd in een verzameling **proposities die door theorie worden ondersteund.** Deze proposities zijn *niet bedoeld om te worden getest of gefalsifieerd* omdat het geen hypotheses zijn. Om hypotheses te kunnen formuleren zou er sprake hebben moeten zijn van verwachte en ruimschoots ondersteunde relaties tussen twee of meer theorieën. Dat is hier niet het geval. Deze thesis tracht het aangegeven problem te onderzoeken door geïnformeerde inzichten te ontwikkelen. Het is niettemin de bedoeling dat de proposities nader worden uitgediept in empirische cases. Het resultaat hiervan is een door empirie ondersteunde waardering over hun niveau van plausibiliteit. Dat oordeel voedt vervolgens de aanbevolen vervolgstappen voor onderzoek en praktijk-professionals om op door te bouwen.

Bij de situaties uit de praktijk die beschikbaar waren om cases uit te selecteren waren, op één na, studenten van Master (MSc) niveau betrokken vooral van de faculteit Industrial Design Engineering (IDE). Dit zijn *design-engineering-professionals-to-be* met een goed basis niveau van ontwerpkennis *en* ze staan open om hun arsenaal aan ontwerpaanpakken uit te breiden met aanpakken, methodes en hulpmiddelen. Aan het begin van dit thesis traject zijn ervaren ontwerpers in bedrijven benaderd om interesse te peilen voor hun directe betrokkenheid. Hun reacties waren terughoudend omdat ze twijfelden of ze met voor hen onbekende aanpakken wilden werken. Hun suggestie was om de aanpak eerst vaker uit te proberen. Werken met vergevorderde Master-studenten was daarom de best mogelijke optie. In het uitzonderingsgeval had de onderzoeker directe toegang tot de externe professionals die de leiding hadden in die specifieke praktijksituatie. Zij waren bereid om in retrospect te bespreken hoe een andere aanpak dan zij hadden gevolgd tot andere resultaten had kunnen leiden.

Van de 23 beschikbare situaties uit de praktijk zijn er zeven geselecteerd te dienen als cases die in detail konden worden meegenomen in dit proefschrift (hoofdstuk 4). De selectie was gebaseerd op de mate van toegang tot rijke informatie van hoge kwaliteit over het ontwerp proces en de uitkomsten ervan, relevantie voor het onderzoek (dat wil zeggen dat de resultaten raakten aan één of meerdere proposities) en als bonus of een situatie tijdens de periode waarin het proefschrift werd geschreven onderdeel was van *peer-reviewed* wetenschappelijke publicaties waarvan de PhD-onderzoeker (co)auteur was. De resultaten van de geselecteerde cases zijn door de onderzoeker vastgelegd in de vorm van case-specifieke bevindingen die zijn geclusterd per propositie. Daarbij is een diversiteit aan beschikbare bronnen gebruikt: ontwerpverslagen, vergaderingen, interactie tijdens conferenties en andere communicatie met belanghebbenden, en diepgaande discussie met ontwerp experts in de faculteit. De case-specifieke bevindingen zijn vervolgens gecombineerd in overkoepelende *empirische inzichten per propositie*, 41 in totaliteit, en in verschillende iteraties diepgravend beschouwd door ontwerp experts en professionals uit de praktijk voordat ze definitief zijn gemaakt, zoals ze worden aangeboden in dit proefschrift. De analyse van deze **empirische inzichten per propositie** had tot doel om specifieke of overkoepelende **patronen** te identificeren die waren gerelateerd aan de thema's die waren afgedekt in de **door de theorie ondersteunde proposities.** Hierdoor was het mogelijk om te beoordelen hoe plausibel de proposities waren, en ook hoe ze verder kunnen worden uitgewerkt en uitgediept, gebaseerd op de empirische inzichten. Het was de verwachting dat de patronen meer licht zouden laten schijnen op de mogelijke bijdrage van dit onderzoek aan bestaande theorie en de ontwerppraktijk.

Voornaamste resultaten

De analyse van de eerder genoemde patronen die uit de zeven cases naar voren kwamen leidde tot de volgende voornaamste resultaten (hoofdstuk 5):

- Proposities werden door de bank genomen meer *ondersteund* dan *tegengesproken* door de empirische inzichten (20 tegenover 4). Het totale aantal empirische inzichten dat de proposities ondersteunde was ook iets hoger dan het aantal dat duidde op de *wenselijkheid om proposities anders te formuleren* (20 tegenover 17). Deze aantallen moeten niet worden beschouwd als numeriek bewijs want ze geven niets aan over de verschillen in de sterkte van ondersteuning, tegenspraak of wenselijkheid van herformulering met betrekking tot de proposities. De getallen bieden slechts een eerste blik of de proposities stand hielden wanneer ze tegen praktijksituaties werden aangehouden. Dit geeft een globaal idee over de mate van plausibiliteit van de proposities en geeft richting aan verdere ontwikkeling ervan.
- *Design engineering* studenten bleken, indien ze daartoe werden aangezet, in staat om contexten te variëren voor de ontwerp taak was vastgesteld. In de meeste gevallen was die variatie beperkt tot geografische afbakeningen. Dit impliceert dat hoewel de ontwerp resultaten veelbelovend waren ze mogelijk nog robuuster waren geweest met betrekking tot verschillende toekomstige scenario's als ze ook zouden zijn gebaseerd op andere manieren om relevante contexten voor de ontwerptaak te onderscheiden.

- Door contexten die relevant zijn voor het probleem te variëren was de informatie die moest worden beschouwd binnen de ontwerptaak in groot volume aanwezig, divers en relevant. Dit verkleinde de noodzaak voor de *design engineers* om willekeurige informatie te zoeken die niet directe betrekking had op de ontwerptaak om creatieve verbindingen te maken. De rijkheid van de ontwerpruimte voedde zowel de creativiteit (= identificeren en maken van nieuwe verbindingen) die wordt gestimuleerd door architectuur-denken alsmede de effectiviteit van het ontwerp proces (= bereiken van een wenselijk functioneel resultaat). Deze combinatie werd expliciet ervaren en aangetoond door de studenten in de meeste cases.
- In een aantal cases kon de kwaliteit van het resultaat van het ontwerp proces waarbij de CVD-aanpak was gebruikt worden vergeleken met soortgelijke resultaten van ontwerp processen waarbij CVD niet was gebruikt. In meerdere van deze gevallen, te weten bij resultaten van drie soortgelijke sessies om ontwerpconcepten te genereren, bij *performance* testen van een gasificatie kooktoestel en bij meningen die werden geuit tijdens een sessie met belanghebbenden en experts op het gebied van kooktoestellen, kwamen expliciete signalen naar boven dat het resultaat van de CVD-aanpak superieur werd bevonden aan de soortgelijke uitkomsten zonder de CVD-aanpak. Deze signalen kunnen niet worden geïnterpreteerd als doorslaggevend bewijs maar geven wel aanleiding om deze manier van werken voort te zetten.
- Indien opdrachten werden uitgevoerd die kort duurden (dat wil zeggen dagen in vergelijking met maanden), onder tijdsdruk en zonder expliciet belang, bijvoorbeeld als onderdeel van een vak, waren de mate van waardering, begrip en daadwerkelijke resultaten divers binnen de groep van studenten als geheel. Zelfs in deze omstandigheden gaf een redelijk aantal studenten aan zowel de bedoeling als het potentieel van een aanpak als CVD te waarderen.
- In de meeste gevallen waarin de studenten volledige ontwerp opdrachten uitvoerden, kon de meerderheid van de studenten en hun academische en praktijk-begeleiders meer waardering opbrengen voor het potentieel van de CVD-aanpak. Het werd ook duidelijk dat het proces om tot een adaptieve architectuur te komen zoals verwacht in het begin meer tijd kostte maar dat deze tijd later weer werd teruggepakt omdat de studenten rijkere informatie hadden om op terug te vallen om keuzes te maken. Ze deden er niet per se langer over om de opdracht af te ronden, alleen was de intensiteit gedurende verschillende fasen van het proces anders. Bovendien was als ze CVD hadden gebruikt het potentieel voor schaalbaarheid, vanuit een ontwerp perspectief, duidelijker zodra ze klaar waren met hun opdracht. Hoewel beide soorten gevolgen ook aantrekkelijk zouden moeten zijn vanuit een management perspectief bleek het gedurende de uitvoering van de opdrachten niet eenvoudig voor

mensen in management posities om deze voordelen ook als zodanig te waarderen. Dit zou te maken kunnen hebben met hoe die voordelen precies worden geformuleerd. Dezelfde uitdaging kan worden voorzien met vertegenwoordigers van andere inhoudelijke domeinen. Dat aspect verkennen zat echter niet in de scope van deze thesis.

- Daarom is het in lijn brengen van de ontwerp en management perspectieven relevant. Beide vakgebieden hebben verschillende prioriteiten en gebruiken andere dominante formuleringen. De cases en het onderzoek als geheel hebben een aantal ideeën opgeleverd welke formuleringen zouden kunnen worden gebruikt om ze meer in lijn met elkaar te brengen. Als aanvullend resultaat werd duidelijk dat wanneer de ontwerpuitdaging multi-contextueel is, een ontwerpteam waarin verschillende vaardigheden worden gecombineerd waarschijnlijk beter presteert.

Conclusies

Deze resultaten geven aanleiding tot een verbeterde versie van CVD, 2.0. Deze upgrade verandert weinig aan de fundamenten zoals uiteengezet voor CVD 1.0, maar kan worden beschouwd als een aanscherping van de nadruk en formulering van bepaalde aspecten. De voornaamste elementen van de upgrade worden hieronder benoemd, geclusterd volgens de voornaamste invalshoeken van het onderzoek.

- **Design engineering arsenaal:** een beter begrip van de belangrijkste gedefinieerde constructen:
  - **Contexten** kunnen worden onderscheiden op verschillende manieren die relevant zijn voor de ontwerptaak. Het is wenselijk om meer tijd te besteden aan het onderzoeken wat de sleutel dimensies van het probleem zijn die kunnen helpen om contexten te kiezen die *relevant zijn voor het ontwerp*. Door dit vroegtijdig te doen wordt het daadwerkelijke ontwerp proces zowel breed (oftewel dekt meerdere contexten af) als gericht (relevante contextuele keuzes worden gemaakt). Dit bespaart moeite omdat geen informatie hoeft te worden gehaald uit *willekeurige contexten die niet relevant zijn voor de ontwerptaak*. Het is wenselijk om dit expliciet te benadrukken aan *design engineers* om het risico te verminderen dat ze te snel kiezen voor de meest voor de hand liggende contexten die echter niet de diversiteit van het probleem voldoende afdekken.
  - **Rijkheid** in een ontwerpruimte wordt bepaald door de hoeveelheid informatie (‘resolutie’) die inherent relevant is (‘focus’). Omdat CVD zowel het volume als de relevantie van de informatie in de ontwerpruimte stimuleert ,vergroot de aanpak het potentieel om superieure resultaten van het ontwerp proces te bereiken die inherent (creatieve) wederzijdse verbanden meenemen tussen de

contexten die relevant zijn voor het ontwerp. Zelfs een dergelijke rijke ontwerp ruimte bevat niet alle informatie die niet-ontwerp gerelateerde uitdagingen afdekken. Niettemin is het in een rijke ontwerp ruimte wel waarschijnlijk dat informatie naar boven komt die hints oplevert over mogelijke uitdagingen die verwacht kunnen worden bij implementatie op grote schaal, ook als die buiten het domein voor ontwerpers liggen.

- Om bij een breder publiek te resoneren kan het zinvol zijn om de **adaptieve architectuur** voor te stellen als een productfamilie. Een manier om dat mogelijk effectief te communiceren is om die architectuur te presenteren als een drie-lagen model, te weten een laag met generieke of *no regret*' componenten, een laag met aanpasbare modules en een laag met context-specifieke componenten. Dit zou de boodschap kunnen helpen overbrengen dat iedere product versie voor een specifieke context deels gelijk is aan versies voor andere contexten. Bij het alternatief in de vorm van een configureerbaar platform dat is gebaseerd op eisen van een initiële context zijn de keuzes met betrekking tot flexibiliteit gebaseerd op aannames. In geval voor een volledig flexibel product platform zou zijn gekozen, zou dat resulteren in over-dimensionering (alles moet mogelijk zijn) en feitelijk neerkomen op het niet maken van welke keus dan ook.

▪ **Empirische invalshoek, (potentieel voor) grootschalige impact, management overwegingen:**

- De signalen voor de superioriteit van de ontwerpresultaten van een proces waarin CVD wordt gebruikt in de context van grootschalige duurzaamheidsvraagstukken kwamen in meerdere cases naar voren. Die superioriteit verwijst naar de ervaren kwaliteit door bijvoorbeeld opdrachtgevers, medestudenten, experts en de uitkomsten van een vergelijkende *performance* test. Het zou te ver gaan om dit te beschouwen als doorslaggevend bewijs voor de superioriteit van de aanpak en dit was ook niet het doel van dit inductieve proefschrift. Om het materiaal te verzamelen om conclusies te kunnen trekken voor een dergelijk bewijs zou een systematische opzet vergen, resulerend in grote hoeveelheden data uit volledig vergelijkbare cases. Dat is slecht denkbaar in de daadwerkelijke ontwerp-praktijk.
- CVD biedt een systeem-georiënteerd perspectief, wat verder zou kunnen worden ondersteund door sterke samenwerking van professionals met verschillende achtergronden, ook binnen het ontwerpteam.
- Om voorwaarden te scheppen waarbinnen een aanpak zoals CVD gedijt, zouden managers meer aanvullende meet-indicatoren moeten gebruiken die op de langere termijn zijn gericht. Deze zouden dan compenseren voor degene die zich alleen

richten op de korte termijn zoals initiële time-to-market en kwartaalverkoopcijfers. Het onderzoek kon niet dusdanig worden uitgebreid dat de acceptatie van het gebruik van meer lange termijn georiënteerde meet-indicatoren in de praktijk kon worden verkend.

- **Empirische invalshoek. Implicatie voor design engineering onderwijs**:
  - Het onderzoek en de cases hebben aangetoond dat de CVD-aanpak een relevante uitbreiding is van het bestaande arsenaal van methodes dat wordt aangeboden in *design engineering* onderwijs. Versie 2.0 bevat meerdere veranderingen qua formulering en communicatie die een effectief gebruik van de CVD-aanpak zouden moeten faciliteren. Tegelijkertijd, zoals ook kan worden afgeleid uit de cases, is het legitiem om te beweren dat niet alle *design engineers-to-be* rollen kunnen of zelfs zouden moeten willen bekleden waarbij ze bezig moeten zijn met multi-contextuele complexiteit. De reikwijdte van rollen voor ontwerpers is groot genoeg om ruimte te bieden aan verschillende soorten vaardigheden, lopend van nadruk op vormgeving, via pure product ontwikkeling tot meer strategische rollen.
  - Het blijkt dat het relevant is om te beseffen dat *design engineering* ook met een systemisch perspectief en aandacht voor meerdere contexten nog steeds niet alles afdekt. Ontwerp is een belangrijke, maar niet enige, component van een breder proces om te proberen bij te dagen aan een betere maatschappij. Ontwerp docenten moeten wellicht een goede balans vinden om zowel het belang van het vak over te brengen, als de noodzaak dat *design engineers* beseffen dat ze bescheiden genoeg moeten zijn om met anderen samen te werken om een werkelijk positieve invloed op de maatschappij te hebben.

Vervolg

De resultaten bieden openingen voor meerdere richtingen voor volgende stappen, waarvan de voornaamste hier in verkorte vorm worden aangegeven. Over het algemeen zullen die volgende stappen ook op een inductieve manier moeten plaatsvinden, zoals gepast is voor ontwerponderzoek. Ze zijn geclusterd in termen van de voornaamste invalshoeken zoals die door het hele proefschrift zijn gebruikt.

- **Design engineering arsenaal:** “De rijkdom van rijkheid”. Verken de ontwikkeling van rijkheid als gedefinieerd construct in de ontwerp ruimte verder en hoe dit bij kan dragen aan superieure resultaten van het ontwerp proces.

- **Grootschalige duurzaamheidsimpact:** “Ga voor Goud”. Ga een meerjarig commitment aan met belanghebbenden om de lange termijn potentie (implementatie en impact in meerdere contexten) daadwerkelijk in de praktijk te kunnen onderzoeken. Het is denkbaar dat het dan nodig is om ook aspecten buiten het domein van design engineering explicieter aandacht te geven.
- **Management alignment:** “C’est le ton qui fait la musique”. Onderzoek de (formulering van) noties die bij managers resoneren om hun prioriteiten in lijn te brengen met die van *design engineers* om de kans te vergroten dat grootschalige duurzaamheidsimpact daadwerkelijk wordt bereikt. Hetzelfde geldt in feite voor in lijn brengen van formuleringen met professionals uit andere domeinen.
- **Design engineering onderwijs:** “Laat geen Leonardo achter”. Verken verder welke type(n) begeleiding, supervisie en voorwaarden geschikt zijn om multi-contextuele aanpakken in onderwijs aan te moedigen. Dit omvat ook de verkenning of openheid voor zulke aanpakken een zinvolle indicator is voor de toekomstige rol die een *design engineering* student zou kunnen ambiëren.

Acknowledgements &
About the Author

Acknowledgements

So, this is it. The culmination of several years of work, with the summit of the mountain reached exactly 500 years after one of its main inspirers, Leonardo da Vinci stopped breathing. In an ideal world I would have defended this thesis exactly 500 years after his departure to the day (May 2nd 2019). In the real world, the bulk of the writing got done in the 500th celebratory year. Good enough.

Even more so because the contribution of the dead to producing a PhD-thesis can only go so far. Many people who *are* still alive have been important in this journey. I will not mention many names, because that would not be fair on the people I might forget here. Or formulated differently, I'll mention the 'patterns' instead of the data points, which seems fitting given the topic of this thesis.

So many people played a role in this process, from the colleagues in the first projectwhen I joined, the prelude-period, the PhD-years, colleagues at my parallel jobs (past and present), my friends (you know who you are), and to mention one person in particular, Udo, who found the time and energy to review my entire thesis. You all have a thing in common: within the boundaries of human capacity you tolerated my frequent word-storms without thumping me on the nose. Also on behalf of my nose, thank you for that. In doing so you demonstrated one main notion of this thesis: focus on the Big Picture, instead of prematurely pressing for the details. Again, it's about the patterns, not the single points. More concretely in this case, the main pattern that you seemed to have recognised was: I very much liked what I was working on, time permitting others might get some use out of it and in the meantime it's clear that there is passion. Good enough.

And now I'm at it, of course I have to thank my supervisory team. With names, in chronological order: Marcel Crul who enabled me to play around in the sandbox of emerging opportunities, Jo van Engelen who recognised that if you facilitate curious playfulness in the right way wonderful and hopefully lasting castles can be built and JC Diehl who made sure the castles were firmly rooted in sand, not air. The combination of your styles and strengths, separately and every time we met, made all this possible. Your joint supervision efforts represented one of the other core elements of this thesis: diversity rocks. And you allowed me to roll, at my own speed and with my own twists and turns as we moved forward. Some of these in the end were more relevant than others, but they all contributed to the journey that a PhD-process is supposed to be.

Of course, as obvious as worthy of mentioning, this work would not have been possible if the diversity traits of my parents would not have merged. If not by design then at least by wonderful fortune. My father did not see this result, my mother I am guessing might see it through slightly watery but

certainly proud eyes. There is no formula or AI-tool in the world that could have predicted or concocted this outcome. There are still some things you cannot put in an algorithm…

It's done. You have all been witnesses to (parts of) the process. Now a new chapter begins, of applying the lessons of this thesis in new circumstances. Feel free to do so yourselves as well.

About the Author

True to form, Wouter's career, academic and otherwise, has been far from a straight line. In fact it hardly ever was one line. One of the main themes of this thesis, i.e., the value of sourcing in different (contextual) perspectives, as it turns out is mirrored in his career path and that might not be a coincidence. Wouter was born in 1972 and raised in Den Haag, the Netherlands, where he eventually spent most of his life. If you think "So where are the different perspectives", read on.

His career spans over 20 years in profit, non-profit and academic environments, for the past fifteen years almost the entire period with two jobs in parallel (academic and non-academic) at any given time. These continuous different "contexts" turned making (new) connections in an automatic red thread in his work related floral bouquet. The change towards this type of career governed by broad instead of narrow interest by then was "perfectly illogical" after an MSc in Industrial Engineering & Management from University of Twente, five years of working at a Telecoms consultancy company. and an MSc in Environmental Science from University of Greenwich.

That's when it started to become confusing for the outside world. Broadness reigned: research on climate change (policy), media attention due to calamities, labour migration, making the financial system more sustainable, parallel (non-academic) work helping to set up and develop Enviu (setting up scalable social enterprises worldwide), his role evolved into "innovation manager". His own preferred title: "Chief (professional) Curiosity".

The vision of professional curiosity as cornerstone for any meaningful innovation became the driver of a solo-attempt to make the world a better place from 2018 onwards, while still continuing the PhD that had started part-time in the summer of 2016. The privately professional endeavour (The New ABC) resulted in contributions to a few brave efforts of educators to incorporate creativity in their curriculum. Companies turned out to be less eager to spend more time on formulating better questions instead of storming ahead to easy answers.

The part-time PhD turned out to be a very good way to at least apply the vision of professional curiosity himself, independent of reluctant managers in doomed companies (semi-smiley face). This combination of curiosity-driven creativity together with a vision and supporting research also go together very nicely at his current job at Platform31, addressing local and regional issues, in particular regarding the circular economy.

And this is where we are now. A brief history of the value of creating a personal environment where new connections occur, planned and unplanned, intentional, but remaining flexible enough to adapt.

References

References

ABDELNOUR, S. 2015. The Cookstove–Rape Prevention Myth and the Limits of Techno-saviorism. *Sustainable Access to Energy in the Global South.* Springer.

ACKOFF, R. L. 1971. Towards a system of systems concepts. *Management science*, 17, 661-671.

ACKOFF, R. L. 1973. Science in the systems age: beyond IE, OR, and MS. *Operations research*, 21, 661-671.

AGARWAL, N., GROTTKE, M., MISHRA, S. & BREM, A. 2017. A systematic literature review of constraint-based innovations: State of the art and future perspectives. *IEEE Transactions on Engineering Management*, 64, 3-15.

ALLEN, P. M. 1998. Evolving complexity in social science. *Systems: New paradigms for the human sciences*, 3-38.

ANCONA, D., BACKMAN, E. & ISAACS, K. 2019. Nimble leadership. Walking the line between creativity and chaos. *Harvard Business Review*, 97, 74-89.

ANDERSSON DJURFELDT, A. 2015. Multi-Local Livelihoods and Food Security in Rural Africa. *Journal of International Development*, 27, 528-545.

ARGYRIS, C. 1976. Single-loop and double-loop models in research on decision making. *Administrative science quarterly*, 363-375.

ARGYRIS, C. 1977. Double loop learning in organizations. *Harvard business review*, 55, 115-125.

ASSEMBLY, U. G. 2014. Report of the open working group of the General Assembly on Sustainable Development Goals. *General Assembly Document A/69/970, New York*, 12.

AULAKH, P. S., ROTATE, M. & TEEGEN, H. 2000. Export strategies and performance of firms from emerging economies: Evidence from Brazil, Chile, and Mexico. *Academy of management Journal*, 43, 342-361.

BACKX, J., HILBERATH, C., MESSENBOCK, R., MORIEUX, Y. & STREUBEL, H. 2017. Mastering complexity through simplification: Four steps to creating competitive advantage. February ed.

BALDASSARRE, B., CALABRETTA, G., BOCKEN, N., DIEHL, J. & KESKIN, D. 2019. The evolution of the Strategic role of Designers for Sustainable Development. *Research perspectives in the era of transformations.* London, UK: Academy for Design innovation Management.

BANERJEE, A., BANERJI, R., BERRY, J., DUFLO, E., KANNAN, H., MUKERJI, S., SHOTLAND, M. & WALTON, M. 2017. From proof of concept to scalable policies: Challenges and solutions, with an application. *Journal of Economic Perspectives*, 31, 73-102.

BARTH, T. 2018. Drawing - Special Issue (Editorial). *Form Akademisk-Research Journal of Design and Design Education*, 11, 1-16.

BEITZ, W. & PAHL, G. 1992. *Engineering design: a systematic approach*, London, The Design Council.

BENAVENTE, D., DUTTA, S. & WUNSCH-VINCENT, S. 2012. The Global Innovation Index 2012: Stronger Innovation Linkages for Global Growth. *The Global Innovation Index 2012: Stronger Innovation Linkages for Global Growth*, 3-78.

BENNETT, N. & LEMOINE, G. J. 2014. What a difference a word makes: Understanding threats to performance in a VUCA world. *Business Horizons*, 57, 311-317.

BERKHOUT, F. 2002. Technological regimes, path dependency and the environment. *Global environmental change*, 12, 1-4.

BHADURI, S. 2016. *Frugal Innovation by'the Small and the Marginal': An Alternative Discourse on Innovation and Development*, Erasmus University Rotterdam.

BHATTI, Y. A. 2012. What is frugal, what is innovation? Towards a theory of frugal innovation. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2005910.

BIELECKI, C. & WINGENBACH, G. 2014. Rethinking improved cookstove diffusion programs: A case study of social perceptions and cooking choices in rural Guatemala. *Energy Policy*, 66, 350-358.

BJÖGVINSSON, E., EHN, P. & HILLGREN, P.-A. 2012. Design things and design thinking: Contemporary participatory design challenges. *Design Issues*, 28, 101-116.

BLIZZARD, J. L. & KLOTZ, L. E. 2012. A framework for sustainable whole systems design. *Design Studies*, 33, 456-479.

BOCKEN, N. M., FIL, A. & PRABHU, J. 2016. Scaling up social businesses in developing markets. *Journal of Cleaner Production*, 139, 295-308.

BODANSKY, D. 2003. Climate Commitments-Assessing the Options. *Pew Center for Global Climate Change*.

BOEIJEN, A. G. C., DAALHUIZEN, J. J., ZIJLSTRA, J. J. M. & VAN DER SCHOOR, R. S. A. 2014. *Delft Design Guide: design strategies and methods*, Amsterdam, BIS Publishers.

BRADACH, J. L. 1997. Using the plural form in the management of restaurant chains. *Administrative Science Quarterly*, 42, 276-303.

BREM, A. & WOLFRAM, P. 2014. Research and development from the bottom up-introduction of terminologies for new product development in emerging markets. *Journal of Innovation and Entrepreneurship*, 3, 9.

BROWN, J. S. & HAGEL III, J. 2005. Innovation blowback: Disruptive management practices from Asia. *The McKinsey Quarterly*, 35-45.

BROWN, T. 2008. Design Thinking. *Harvard Business Review*, 86, 84-92.

BROWN, T. 2009. *Change by design: How design thinking creates new alternatives for business and society*, Collins Business.

BUCHANAN, R. 1992. Wicked problems in design thinking. *Design issues*, 8, 5-21.

BUIJS, J. The Delft Innovation Method A Design Thinker's Guide to Innovation. DS 71: Proceedings of NordDesign 2012, the 9th NordDesign conference, Aarlborg University, Denmark. 22-24.08. 2012, 2012.

BUSHE, G. R. 2013. Generative process, generative outcome: The transformational potential of appreciative inquiry. *Organizational generativity: The appreciative inquiry summit and a scholarship of transformation.* Emerald Group Publishing Limited.

CALABRETTA, G., GEMSER, G. & KARPEN, I. 2016. *Strategic Design: Eight essential practices every strategic designer must master*, BIS Publishers.

CAMACHO, M. 2018. An Integrative Model of Design Thinking. *21st DMI: Academic Design Management Conference.* London, UK.

CAMPANARIO, J. M. 2009. Rejecting and resisting Nobel class discoveries: accounts by Nobel Laureates. *Scientometrics*, 81, 549-565.

CANTWELL, J. 1995. The globalisation of technology: what remains of the product cycle model? *Cambridge journal of economics*, 19, 155-155.

CESCHIN, F. & GAZIULUSOY, I. 2016. Evolution of design for sustainability: From product design to design for system innovations and transitions. *Design Studies*, 47, 118-163.

CHECKLAND, P. 1981. *Systems thinking, systems practice*, Chichester, John Wikey & Sons.

CHEN, C.-C. & CRILLY, N. 2016. From modularity to emergence: a primer on the design and science of complex systems. https://doi.org/10.17863/CAM.4503.

COLLOPY, F. 2009. Lessons learned–Why the failure of systems thinking should inform the future of design thinking. *Fast Company blog* [Online]. Available from: www.fastcompany.com/1291598/lessons-learned-why-failure-systems-thinking-should-inform-future-design-thinking.

COONRAD, J. 2014. MDGs to SDGs: Top 10 Differences. The Hunger Project: Global Advocacy.

COOPER, R. G. 2008. The stage-gate idea-to-launch process–update, what's new and NexGen systems. *Journal of Product Innovation Management*, 25, 213-232.

COOPER, R. G. 2014. What's Next?: After Stage-Gate. *Research-Technology Management*, 57, 20-31.

CORSI, S. 2012. *Reversing the international flow of innovation: How does the Chinese market trigger reverse innovation.* PhD thesis. Scuola Superiore Sant'Anna.

CROPLEY, D. & CROPLEY, A. 2005. Engineering creativity: A systems concept of functional creativity. *Creativity across domains: Faces of the muse*, 169-185.

CROSS, N. 2001. Designerly ways of knowing: Design discipline versus design science. *Design issues*, 17, 49-55.

D'SOUZA, S. & RENNER, D. 2014. *Not knowing: The art of turning uncertainty into opportunity*, LID Editorial.

DA COSTA JUNIOR, J., DIEHL, J. C. & SNELDERS, D. 2019. A framework for a systems design approach to complex societal problems. *Design Science*, 5.

DAHLMAN, C. J., ROSS-LARSON, B. & WESTPHAL, L. E. 1987. Managing technological development: lessons from the newly industrializing countries. *World development*, 15, 759-775.

DAVIS, J. 2013. How a radical new teaching method could unleash a generation of geniuses. *Wired Business, [online]: http://www.wired. com/2013/10/ free-thinkers.*

DE JONG, J. P. & DE BRUIJN, E. 2013. Innovation lessons from 3-D printing. *MIT Sloan Management Review*, 54, 43.

DEATON, A. 2013. *The great escape: health, wealth, and the origins of inequality*, Princeton University Press.

DEIGLMEIER, K. & GRECO, A. 2018. Wht proven solutions strugle to scale up. Available from: https://ssir.org/articles/entry/ why_proven_solutions_struggle_to_scale_up# [Accessed 12 October 2018].

DENNETT, D. C. 2017. *From bacteria to Bach and back: The evolution of minds*, WW Norton & Company.

DIEHL, J., VAN SPRANG, S., ALEXANDER, J. & KERSTEN, W. 2018. A scalable clean cooking stove matching the cooking habits of Ghana and Uganda *Global Humanitarian Technology Conference.* San Jose, CA: IEEE.

DIETHELM, J., FLANNERY, J. E., GIULIANI, N. R., FLOURNOY, J. C. & PFEIFER, J. H. 2016. De-Colonizing Design Thinking. *She Ji: The Journal of Design, Economics, and Innovation*, 2, 166-172.

DIJK, M., DA SCHIO, N., DIETHART, M., HOFLEHNER, T., WLASAK, P., CASTRI, R., CELLINA, F., BOUSSAUW, K., CASSIERS, T., CHEMIN, L., CORVERS, R., DE KRAKER, J., KEMP, R. & VAN HEUR, B. 2019. How to anticipate constraints on upscaling inclusive Living Lab experiments, SmarterLabs project 2016 -2019. JPI Urban Europe: JPI Urban Europe.

DIJK, M., DE KRAKER, J. & HOMMELS, A. 2018. Anticipating Constraints on Upscaling from Urban Innovation Experiments. *Sustainability*, 10.

DORAN, G. T. 1981. There'sa SMART way to write management's goals and objectives. *Management review*, 70, 35-36.

DORST, K. 2006. *Understanding design. 175 reflections on being a designer*, Amsterdam, BIS Publishers.

DORST, K. 2015. *Frame innovation: Create new thinking by design*, Cambride, Massachusetts; London, England, MIT Press.

DORST, K. & CROSS, N. 2001. Creativity in the design process: co-evolution of problem–solution. *Design studies*, 22, 425-437.

DUNNE, D. & MARTIN, R. 2006. Design thinking and how it will change management education: An interview and discussion. *Academy of Management Learning & Education*, 5, 512-523.

DUNNE, D. D. & DOUGHERTY, D. 2012. Chapter 22. Organizing for change, innovation and creativity. *Handbook of organizational creativity. Elsevier Inc.* Elsevier, Academic Press imprint.

EISENHARDT, K. M. & PIEZUNKA, H. 2011. Complexity theory and corporate strategy. *The SAGE handbook of complexity and management*, 506-523.

ELKINGTON, J. 1998. Partnerships from cannibals with forks: The triple bottom line of 21st-century business. *Environmental Quality Management*, 8, 37-51.

ERKENS, A. 1928. Beitrage zur Konstruktionserziehung. *Z. VDI*, 72, 17-21.

ESMAP 2015. The state of the global and improved cooking sector. Technical report 007/15. Washington DC: Energy Sector Management Assistance Program.

FALZON, M.-A. 2016. *Multi-sited ethnography: Theory, praxis and locality in contemporary research*, Routledge.

FERGUSON, N. 2008. *The ascent of money: A financial history of the world*, Penguin.

FERGUSON, N. 2017. *The Square and the Tower: Networks, Hierarchies and the Struggle for Global Power*, Penguin UK.

FINDEISEN, D. 1974. *Dynamisches System Schwingprüfmaschine: Vergleich verschiedener Systemvarianten*, VDI-Verlag.

FLACH, J. M. 2015. Supporting self-designing organizations. *Journal of Design, Economics and Innovation*, 1, 95-99.

FRANKOPAN, P. 2015. *The silk roads: A new history of the world*, Bloomsbury Publishing.

FRANKOPAN, P. 2019. *The new silk roads: the present and future of the world*, Knopf.

FURR, N., NEL, K. & RAMSOY, T. Z. 2018. If your innovation effort isn't working, look at who's on the team. *Innovation* [Online]. Available from: https://hbr.org/2018/11/if-your-innovation-effort-isnt-working-look-at-whos-on-the-team [Accessed 23 November 2018 2018].

GACC 2016. Clean cooking key to development and climate goals. 2016 progress report. GACC: GACC.

GAZIULUSOY, A. İ. & RYAN, C. 2017. Shifting conversations for sustainability transitions using participatory design visioning. *The Design Journal*, 20, S1916-S1926.

GELB, M. J. 2009. *Think like da Vinci*, Hammersmith. London, HarperCollins.

GEORGE, G., MCGAHAN, A. M. & PRABHU, J. 2012. Innovation for Inclusive Growth: Towards a Theoretical Framework and a Research Agenda. *Journal of Management Studies*, 49, 661-683.

GOLDSTEIN, J. 2000. Emergence: A construct amid a thicket of conceptual snares. *Emergence*, 2, 5-22.

GONÇALVES, M. 2016. *Decoding designers' inspiration process*. PhD, Delft University of Technology.

GONÇALVES, M., CARDOSO, C. & BADKE-SCHAUB, P. 2014. What inspires designers? Preferences on inspirational approaches during idea generation. *Design studies*, 35, 29-53.

GONÇALVES, M., CARDOSO, C. & BADKE-SCHAUB, P. 2016. Inspiration choices that matter: the selection of external stimuli during ideation. *Design Science*, 2.

GOVINDARAJAN, V. & TRIMBLE, C. 2012. Reverse innovation: a global growth strategy that could pre-empt disruption at home. *Strategy & Leadership*, 40, 5-11.

GRIFFIN, D., SHAW, P. & STACEY, R. 1998. Speaking of complexity in management theory and practice. *Organization*, 5, 315-339.

GULATI, R. 2018. Structure that's not stifling. *Harvard Business Review*, 96, 68-79.

HAGEL III, J. & BROWN, J. S. Globalization & innovation: some contrarian perspectives. Prepared for the annual meeting of the World Economic Forum in Davos, Switzerland, 2006. 25-30.

HANSEN, F. 1965. *Konstruktionssystematik: Grundlagen für eine allgemeine Konstruktionslehre*, Verlag Technik.

HANSEN, F. 1974. *Konstruktionswissenschaft: Grundlagen und Methoden*, Hanser.

HARINCK, F., VAN DIJK, E., VAN BEEST, I. & MERSMANN, P. 2007. When gains loom larger than losses: Reversed loss aversion for small amounts of money. *Psychological science*, 18**,** 1099-1105.

HARRISON, M. B., GRAHAM, I. D., FERVERS, B. & VAN DEN HOEK, J. 2009. Adapting knowledge to a local context. *Knowledge translation in health care: Moving from evidence to practice***,** 73-82.

HART, S. & PRAHALAD, C. 2002. The Fortune at the Bottom of the Pyramid. *Strategy+ business*, 26**,** 54-67.

HARTMANN, A. & LINN, J. F. 2008. Scaling up: a framework and lessons for development effectiveness from literature and practice.

HINE, C. 2007. Multi-sited ethnography as a middle range methodology for contemporary STS. *Science, Technology & Human Values*, 32**,** 652-671.

HOPPE, T., GRAF, A., WARBROEK, B., LAMMERS, I. & LEPPING, I. 2015. Local governments supporting local energy initiatives: Lessons from the best practices of Saerbeck (Germany) and Lochem (The Netherlands). *Sustainability*, 7**,** 1900-1931.

HÜSIG, S. & KOHN, S. 2003. Factors influencing the front end of the innovation process: A comprehensive review of selected empirical NPD and explorative FFE studies. *Proceedings of the 10th IPDMC***,** 14.

HUSIG, S., KOHN, S. & POSKELA, J. The role of process formalisation in the early phases of the innovation process. Proceedings of the 12th International Product Development Management Conference, 2005. 857-870.

IDELER, L. 2006. *An adoptable woodstove for the Bottom of the Pyramid in rural India.* MSc, Delft University of Technology.

IMMELT, J. R., GOVINDARAJAN, V. & TRIMBLE, C. 2009. How GE is disrupting itself. *Harvard business review*, 87**,** 56-65.

IÑIGO, E. A. & ALBAREDA, L. 2016. Understanding sustainable innovation as a complex adaptive system: a systemic approach to the firm. *Journal of Cleaner Production*, 126**,** 1-20.

ISAACSON, W. 2017. *Leonardo da Binci*, New York, Simon & Schuster.

JOHANSSON-SKÖLDBERG, U., WOODILLA, J. & ÇETINKAYA, M. 2013. Design thinking: past, present and possible futures. *Creativity and Innovation Management*, 22**,** 121-146.

JOHNSON, S. 2002. *Emergence*, New York, Scribner.

JOHNSON, S. 2011. *Where good ideas come from: the seven patterns of innovation*, Penguin UK.

JONES, P. 2014. Systemic design principles for complex social systems. *In:* METCALF, G. S. (ed.) *Social systems and design.* Tokyo: Springer.

JONES, P. 2015. Designing for X: The challenge of complex socio-X system. *Journal of Design, Economics and Innovation*, 1**,** 101-104.

JONES, P. & BOWES, J. 2017. Rendering Systems Visible for Design: Synthesis Maps as Constructivist Design Narratives. *She Ji: The Journal of Design, Economics, and Innovation*, 3**,** 229-248.

JURAN, J. M. & GRYNA, F. M. 1980. *Quality planning and analysis*, McGraw-Hill.

KANDACHAR, P., DE JONGH, I. & DIEHL, J. 2009. Designing for Emerging Markets. *Design of Products and Services. Delf University of Technology*.

KANDACHAR, P., DIEHL, J. C., PARMAR, V. & SHIVARAMA, C. K. 2011. Designing with emerging markets–design of products and services (2011 edition. *Delft University of Technology, Delft*.

KAPLINSKY, R. 2011. Schumacher meets Schumpeter: Appropriate technology below the radar. *Research Policy*, 40**,** 193-203.

KAUFMAN, S. B. & GREGOIRE, C. 2016. *Wired to create: Unraveling the mysteries of the creative mind*, Penguin.

KERSTEN, W., DIEHL, J. & VAN ENGELEN, J. 2018a. Putting the horse in front of the wagon. *In:* SEVALDSON, B. (ed.) *Relating Systems Thinking and Design (RSD6) Symposium 18-20 October.* Oslo, Norway.

KERSTEN, W., DIEHL, J. C. & VAN ENGELEN, J. 2018b. Facing complexity through varying the clarification of th design task. *FormAkademisk*, 11**,** 1-28.

KERSTEN, W. C., CRUL, M. R., DIEHL, J. C. & VAN ENGELEN, J. M. 2015. Context Variation by Design, working paper version 4.0. https://doi.org/10.5281/zenodo.3472365: Delft University of Technology.

KERSTEN, W. C. & DIEHL, J. 2015. Full scale inclusiveness: designing solutions for a complex world. *Workshop When can frugal innovations become inclusive innovations.* The Hague, The Netherlands: CFIA & EADI.

KERSTEN, W. C., DIEHL, J. C. & CRUL, M. R. M. 2017a. Influence of Context Variation on Quality of Solutions: Experiences with Gasifier Stoves. *Procedia Manufacturing*, 8**,** 487-494.

KERSTEN, W. C., DIEHL, J. C., CRUL, M. R. M. & VAN ENGELEN, J. M. L. 2016. A multi-context design approach for a portable ultrasound device. DS 85-1: *Proceedings of NordDesign 2016, Volume 1, Trondheim, Norway, 10th-12th August 2016.*

KERSTEN, W. C., DIEHL, J. C. & VAN ENGELEN, J. M. L. 2018c. Using a multi-context design approach as manifestation of complexity: perceptions and experiences of students in design engineering. *Journal of Design Research*, 16, 33.

KERSTEN, W. C., DIEHL, J. C. & VAN ENGELEN, J. M. L. 2019a. Intentional Design for Diversity as Pathway to Scalable Sustainability Impact. *Innovation for Sustainability*. Springer.

KERSTEN, W. C., DIEHL, J. C. & VAN ENGELEN, J. M. L. 2019b. Making frugal innovations more inclusive by embracing complexity (working paper). https://doi.org/10.5281/zenodo.3361495: Delft University of Technology.

KERSTEN, W. C., LONG, N. H., DIEHL, J. C., CRUL, M. R. M. & VAN ENGELEN, J. M. L. 2017b. Comparing Performance of Biomass Gasifier Stoves: Influence of a Multi-Context Approach. *Sustainability*, 9, 1140.

KESSERLING, F. 1951. *Bewertung von Konstruktionen*, Deutschen Ingenieur-Verlag.

KHANDELWAL, M., HILL JR, M. E., GREENOUGH, P., ANTHONY, J., QUILL, M., LINDERMAN, M. & UDAYKUMAR, H. 2017. Why have improved cook-stove initiatives in India failed? *World Development*, 92, 13-27.

KHANNA, T. 2014. Contextual intelligence. *Harvard Business Review*, 92, 58-68.

KIM, J. & WILEMON, D. 2002. Focusing the fuzzy front–end in new product development. *R&D Management*, 32, 269-279.

KIM, J. & WILEMON, D. 2003. Sources and assessment of complexity in NPD projects. *R&D Management*, 33, 15-30.

KLEIN, G. & JAROSZ, A. 2011. A naturalistic study of insight. *Journal of Cognitive Engineering and Decision Making*, 5, 335-351.

KOFFKA, K. 2013. *Principles of Gestalt psychology*, Routledge.

KOH, H., HEGDE, N. & KARAMCHANDANI, A. 2014. *Beyond the Pioneer: Getting inclusive industries to scale*.

KOLLER, R. 1973. Eine algorithmisch-physikalisch orientierte Konstruktionsmethodik. VDI-Z, 115, 147-152.

KOLLER, R. 1976. Konstruktionsmethode für den Maschinen-, Geräte-und Apparatebau. Hochschultext. Springer-Verlag, Berlin.

KORN, M. & SILVERMAN, R. E. 2012. Forget B-School, D-school is hot. *Wall Street Journal*, 7 June.

KRAMER, N. J. T. A. & DE SMIT, J. 1979. *Systeemdenken - Inleiding tot de begrippen en concepten*, Leiden, Stenfert Kroese BV.

KRATZER, J., LEENDERS, R. T. A. J. & VAN ENGELEN, J. M. L. 2010. The social network among engineering design teams and their creativity: A case study among teams in two product development programs. *International Journal of Project Management*, 28**,** 428-436.

LASZLO, E. 1996. *Evolution: The general theory*, Hampton Press.

LATOUR, B. 2009. Spheres and networks. Two ways to reinterpret globalization. *Harvard Design Magazine***,** 138-144.

LAUDIEN, K. 1931. Maschinenelemente. Dr. Max Junecke Verlagsbuchhandlung, Leipzig.

LE BER, M. J. & BRANZEI, O. 2010. (Re) forming strategic cross-sector partnerships relational processes of social innovation. *Business & Society*, 49**,** 140-172.

LEENDERS, R. T. A., VAN ENGELEN, J. M. & KRATZER, J. 2007. Systematic design methods and the creative performance of new product teams: do they contradict or complement each other? *Journal of Product Innovation Management*, 24**,** 166-179.

LEKE, A. & YEBOAH-AMANKWAH, S. 2018. Africa: A CRUCIBLE for CREATIVITY Lessons from the continent's breakout businesses. *HARVARD BUSINESS REVIEW*, 96**,** 116-125.

LEVY, D. 1994. Chaos theory and strategy: Theory, application, and managerial implications. *Strategic management journal***,** 167-178.

LEYER, A. 1963. Maschinenkonstruktionslehre, Heft 1 (1963), Heft 2 (1964), Heft 3 (1966), Heft 4 (1968). Basel: Birkhäuser.

LICHTENSTEIN, B. B. & PLOWMAN, D. A. 2009. The leadership of emergence: A complex systems leadership theory of emergence at successive organizational levels. *The Leadership Quarterly*, 20**,** 617-630.

LIN, N., CHEN, Y., DU, W., SHEN, G., ZHU, X., HUANG, T., WANG, X., CHENG, H., LIU, J., XUE, C., LIU, G., ZENG, E. Y., XING, B. & TAO, S. 2016. Inhalation exposure and risk of polycyclic aromatic hydrocarbons (PAHs) among the rural population adopting wood gasifier stoves compared to different fuel-stove users. *Atmospheric Environment*, 147**,** 485-491.

LINDGAARD, K. & WESSELIUS, H. 2017. Once More, with Feeling: Design Thinking and Embodied Cognition. *She Ji: The Journal of Design, Economics, and Innovation*, 3**,** 83-92.

LINDSTROM, C. E. 1959. The Science of muddling through. *Public Administration Review*, 19**,** 79-89.

LINSTONE, H. A. 1989. Multiple perspectives: concept, applications, and user guidelines. *Systems practice*, 2**,** 307-331.

LINSTONE, H. A. 1999. *Decision making for technology executives: Using multiple perspectives to improved performance*, Artech House Technology Manage.

LOMBARDI, F., RIVA, F., BONAMINI, G., BARBIERI, J. & COLOMBO, E. 2017. Laboratory protocols for testing of Improved Cooking Stoves (ICSs): A review of state-of-the-art and further developments. *Biomass and Bioenergy*, 98, 321-335.

LONDON, T. & HART, S. L. 2004. Reinventing strategies for emerging markets: beyond the transnational model. *Journal of international business studies*, 35, 350-370.

LOYE, D. & EISLER, R. 1987. Chaos and transformation: Implications of nonequilibrium theory for social science and society. *Behavioral science*, 32, 53-65.

MA, J. A Review of the DesignX Discourse: Knowledge Diffusion and Integration Across Disciplines. International Conference on Human-Computer Interaction, 2019. Springer, 57-78.

MACINTOSH, R. & MACLEAN, D. 1999. Conditioned emergence: A dissipative structures approach to transformation. *Strategic management journal*, 20, 297-316.

MACK, O., KHARE, A., KRÄMER, A. & BURGARTZ, T. 2015. *Managing in a* VUCA *World*, Springer.

MALONE, T. W., LAUBACHER, R. & DELLAROCAS, C. 2010. The collective intelligence genome. *MIT Sloan Management Review*, 51, 21.

MANDELLI, S., BARBIERI, J., MATTAROLO, L. & COLOMBO, E. 2014. Sustainable energy in Africa: A comprehensive data and policies review. *Renewable and Sustainable Energy Reviews*, 37, 656-686.

MARCUS, G. E. 2009. Multi-sited ethnography: Notes and queries. *In:* FALZON, M.-A. (ed.) *Multi-sited ethnography: Theory, praxis, and locality in contemporary research.* Surrey, England: Ashgate publishing.

MARTIN, M. V. & ISHII, K. 2002. Design for variety: developing standardized and modularized product platform architectures. *Research in Engineering Design*, 13, 213-235.

MATOUSEK, R. 1957. *Konstruktionslehre des allgemeinen Maschinenbaues: ein Lehrbuch fur angehende Konstrukteure unter besonderer Berucksichtigung des Leichtbaues*, Springer.

MCELROY, M. W. & VAN ENGELEN, J. M. 2012. *Corporate sustainability management: The art and science of managing non-financial performance*, Routledge.

MEADOWS, D. 1997. Places to Intervene in a System. *Whole Earth*, 91, 78-84.

MEADOWS, D. 2002. Dancing with systems. *Systems Thinker*, 13, 2-6.

MEAGHER, K. & LINDELL, I. 2013. ASR Forum: Engaging with African informal economies: social inclusion or adverse incorporation? *African Studies Review*, 56, 57-76.

MINK, A. 2016. *Design for well-being. An approach for understanding users'lives in Design for Development*. PhD, Delft University of Technology.

MOLL, C. L. & REULEAUX, F. 1854. *Constructionslehre für den Maschinenbau. In zwei Bänden.(Fortgesetzt von F. Reuleaux.)*, Vieweg.

MONAT, J. P. & GANNON, T. F. 2015. What is Systems Thinking? A Review of Selected Literature Plus Recommendations. *American Journal of Systems Science*, 4, 11-26.

MONTUORI, A. 2005. Literature review as creative inquiry: Reframing scholarship as a creative process. *Journal of Transformative Education*, 3, 374-393.

MONTUORI, A. 2011. Beyond postnormal times: The future of creativity and the creativity of the future. *Futures*, 43, 221-227.

MONTUORI, A. 2012. Creative Inquiry: Confronting the challenges of scholarship in the 21st century. *Futures*, 44, 64-70.

MONTUORI, A. 2013. Complexity and transdisciplinarity: Reflections on theory and practice. *World Futures*, 69, 200-230.

MOON, F. C. 2002. Franz Reuleaux: Contributions to 19th C. Kinematics and Theory of. Cornell Library Technical Reports and Papers.

MORIN, E. 2008. *On complexity*, Hampton Press.

MUDAMBI, R., MUDAMBI, S. M. & NAVARRA, P. 2007. Global Innovation in MNCs: The Effects of Subsidiary Self-Determination and Teamwork. *Journal of Product Innovation Management*, 24, 442-455.

MULDER, K. F., SEGALÀS, J. & FERRER-BALAS, D. 2012. How to educate engineers for/in sustainable development: Ten years of discussion, remaining challenges. *International Journal of Sustainability in Higher Education*, 13, 211-218.

MULLER, P. C. 1999. *Team-based conceptualization of new products*. PhD, University of Groningen.

MUNDY, J. 2010. Creating dynamic tensions through a balanced use of management control systems. *Accounting, Organizations and society*, 35, 499-523.

MYERSON, J. 2015. Small Modular steps versus giant creative leaps. *Journal of Design, Economics and Innovation*, 1, 99-100.

NAJAFI-TAVANI, Z., GIROUD, A. & ANDERSSON, U. 2014. The interplay of networking activities and internal knowledge actions for subsidiary influence within MNCs. *Journal of World Business*, 49, 122-131.

NELSON, H. 2007. Simply complex by design. *Performance Improvement Quarterly*, 20, 97-115.

NELSON, H. & STOLTERMAN, E. 2003. *The design way: Intentional change in an unpredictable world: Foundations and fundamentals of design competence*, Educational Technology.

NIEMANN, G. 1950. Maschinenelemente Bd. I, Abschn. IV: Verbindung von Welle und Nabe. Berlin/Göttingen/Heidelberg: Springer.

NIETO, M. J. & SANTAMARÍA, L. 2007. The importance of diverse collaborative networks for the novelty of product innovation. *Technovation*, 27, 367-377.

NIJS, D. 2014. Imagineering the butterfly effect. *Den Haag: Eleven International Publishing*.

NORMAN, D. A. 1988. *The psychology of everyday things*, Basic books.

NORMAN, D. A. 2010. *Living with complexity*, MIT press.

NORMAN, D. A. & STAPPERS, P. J. 2015. DesignX: Complex Sociotechnical Systems. *She Ji: The Journal of Design, Economics, and Innovation*, 1, 83-106.

O'RAFFERTY, S., CURTIS, H. & O'CONNOR, F. 2014. Mainstreaming sustainability in design education–a capacity building framework. *International Journal of Sustainability in Higher Education*, 15, 169-187.

O'SULLIVAN, A. & SHEFFRIN, S. M. 2003. Economics: Principles in action. *Upper Saddle River, New Jersey*, 7458, 246.

OADES-SESE, G. V. & ESQUIVEL, G. B. 2011. Cultural Diversity and Creativity. *Encyclopedia of Creativity*. Elsevier.

OOSTERLAKEN, I. 2009. Design for development: A capability approach. *Design issues*, 25, 91-102.

ORAKLIBEL, R. D., ÜLKEBAS, S. D. & İLHAN, I. O. Creative problem solving assessment and product design education. DS 93: Proceedings of the 20th International Conference on Engineering and Product Design Education (E&PDE 2018), Dyson School of Engineering, Imperial College, London. 6th-7th September 2018, 2018. 282-287.

OSTUZZI, F., DE COUVREUR, L., DETAND, J. & SALDIEN, J. 2017. From Design for One to Open-ended Design. Experiments on understanding how to open-up contextual design solutions. *The Design Journal*, 20, S3873-S3883.

PAGANO, A. 2009. The role of relational capabilities in the organization of international sourcing activities: A literature review. *Industrial Marketing Management*, 38, 903-913.

PAPAIOANNOU, T. 2014. How inclusive can innovation and development be in the twenty-first century? *Innovation and Development*, 4, 187-202.

PAPANEK, V. & FULLER, R. B. 1972. *Design for the real world*, Thames and Hudson London.

PAPANEK, V. & LAZARUS, E. L. 2005. Design for the Real World: Human Ecology and Social Change Ed. 2. Academy Chicago Publishers.

PASCALE, R. T. 1999. Surfing the edge of chaos. *Sloan management review*, 40, 83.

PATON, B. & DORST, K. 2011. Briefing and reframing: A situated practice. *Design Studies*, 32, 573-587.

PEARCE, J. M. 2013. *Open-source lab: how to build your own hardware and reduce research costs*, Newnes.

PEAT, F. D. 2002. *From certainty to uncertainty: the story of science and ideas in the twentieth century*, Washington D.C., Joseph Henry Press.

PEŠA, I. 2017. Sawdust pellets, micro gasifying cook stoves and charcoal in urban Zambia: Understanding the value chain dynamics of improved cook stove initiatives. *Sustainable Energy Technologies and Assessments*.

PETRICK, I. J. & JUNTIWASARAKIJ, S. 2011. The rise of the rest: Hotbeds of innovation in emerging markets. *Research-Technology Management*, 54, 24-29.

PISKURICH, G. M. 2015. *Rapid instructional design: Learning ID fast and right*, John Wiley & Sons.

PLOWMAN, D. A., BAKER, L. T., BECK, T. E., KULKARNI, M., SOLANSKY, S. T. & TRAVIS, D. V. 2007. Radical change accidentally: The emergence and amplification of small change. *Academy of Management Journal*, 50, 515-543.

PRAHALAD, C. K. 2009. *The fortune at the bottom of the pyramid, revised and updated 5th anniversary edition: Eradicating poverty through profits*, FT Press.

PROBST, G. & BASSI, A. 2014. *Tackling complexity: a systemic approach for decision makers*, Greenleaf publishing.

QIU, Y. & FAN, Y. 2013. Rethinking Global Innovation Strategy: Emerging Market Perspectives. *Business and Management Research*, 2, 1-9.

RADJOU, N. 2009. Polycentric Innovation: A New Mandate for Multinationals. *The Wall Street Journal*, 9.

RADJOU, N., PRABHU, J. & AHUJA, S. 2012. *Jugaad innovation: Think frugal, be flexible, generate breakthrough growth*, John Wiley & Sons.

RAMALINGAM, B. 2013. *Aid on the edge of chaos: rethinking international cooperation in a complex world*, Oxford University Press.

RAYNA, T. & STRIUKOVA, L. 2016. From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technological Forecasting and Social Change*, 102, 214-224.

REDTENBACHER, F. J. 1852. *Principien der Mechanik und des Maschinenbaues*, Рипол Классик.

REINERTSEN, D. & SMITH, P. 1991. Developing products in half the time. *New York*, 13.

RIEDLER, A. 1913. Das Maschinenzeichnen und sein sachlicher Zusammenhang mit dem organisierten Maschinenbau. *Das Maschinen-Zeichnen.* Springer.

RIES, E. 2011. *The lean startup: How today's entrepreneurs use continuous innovation to create radically successful businesses*, Crown Business.

RIFKIN, J. 2014. *The zero marginal cost society: The internet of things, the collaborative commons, and the eclipse of capitalism*, St. Martin's Press.

RITTEL, H. W. & WEBBER, M. M. 1973. 2.3 planning problems are wicked. *Polity*, 4, 155-169.

ROBERTS, J. & PEDRETTI, C. 1977. Drawings by Leonardo da Vinci at Windsor newly revealed by ultra-violet light. *The Burlington Magazine*, 119, 396-408.

RODENACKER, W. G. 1976. Methodisches konstruieren. *Methodisches Konstruieren.* Springer.

ROOZENBURG, N. F. & EEKELS, J. 1995. *Product design: fundamentals and methods*, Wiley Chichester.

ROTH, K. 1968. Gliederung und Rahmen einer neuen Maschinen-Geräte-Konstruktionslehre. *Feinwerktechnik*, 72, 521-528.

ROTH, K. 1971. Algorithmisches Auswahlverfahren zur Konstruktion mit Kaoalogen. *Fein-werktechnik*, 75, 337-345.

ROTSCHER, F. 1927. Die Maschinenelemente. *Berlin, Jullus Springer*.

SAAVEDRA, A. R. & OPFER, V. D. 2012. Learning 21st-century skills requires 21st-century teaching. *Phi Delta Kappan*, 94, 8-13.

SARDAR, Z. 2010. Welcome to postnormal times. *Futures*, 42, 435-444.

SARGUT, G. & MCGRATH, R. G. 2011. Learning to live with complexity. *Harvard business review*, 89, 68-76.

SCHÖN, D. A. 1984. *The reflective practitioner: How professionals think in action*, Basic books.

SCHÖN, D. A. & WIGGINS, G. 1992. Kinds of seeing and their functions in designing. *Design studies*, 13, 135-156.

SCHWAB, K. & DAVIS, N. 2018. *Shaping the future of the fourth industrial revolution*, Currency.

SENNETT, R. 2008. *The craftsman*, Yale University Press.

SEVALDSON, B. 2008. Rich design research space. *Form Akademisk-Research Journal of Design and Design Education*, 1, 28-44.

SEVALDSON, B. 2009. Why should we and how can we make the design process more complex. *Fremtid Formes/Shaping Futures. Oslo: Oslo School of Architecture and Design.*

SEVALDSON, B. GIGA-Mapping: Visualisation for complexity and systems thinking in design. Helsinki: Nordic Design Research Conference, 2011.

SEVALDSON, B. Systems Oriented Design: The emergence and development of a designerly approach to address complexity. 2nd International Conference for Design Education Researchers, Oslo, Norway, 2013.

SEVALDSON, B. 2017a. *How to GIGA-map* [Online]. Available: http://www.systemsorienteddesign.net/index.php/giga-mapping/how-to-giga-map) [Accessed 14 January 2018].

SEVALDSON, B. 2017b. Redesigning Systems Thinking. *Form Akademisk-Research Journal of Design and Design Education*, 10, 1-23.

SHEPHARD, R. W. & FÄRE, R. 1974. The law of diminishing returns. *Production theory*. Springer.

SIMON, C. P. & BLUME, L. 1994. *Mathematics for economists*, Norton New York.

SIMON, H. A. 1969. *The sciences of the artificial*, Cambridge, MA, MIT Press.

SMITH, P. G. & REINERTSEN, D. G. 1998. *Developing products in half the time: new rules, new tools*, Wiley.

SNOWDEN, D. J. & BOONE, M. E. 2007. A leader's framework for decision making. *Harvard business review*, 85, 68.

SONI, J. & GOODMAN, R. 2017. *A mind at play: how Claude Shannon invented the information age*, Simon and Schuster.

STACEY, R. D. 1996. *Complexity and creativity in organizations*, San Francisco, CA, Berrett-Koehler Publishers.

STAPPERS, P. J., VAN RIJN, H., KISTEMAKER, S., HENNINK, A. & VISSER, F. S. 2009. Designing for other people's strengths and motivations: Three cases using context, visions, and experiential prototypes. *Advanced Engineering Informatics*, 23, 174-183.

STIGLITZ, J. E. 2008. *Making globalisation work*, Dublin, Esri.

STIRLING, A. 2008. "Opening up" and "closing down" power, participation, and pluralism in the social appraisal of technology. *Science, Technology, & Human Values*, 33, 262-294.

SUEN, P. Conditions that foster an ability to reframe problems. *In:* RYAN, A. & JONES, P., eds. Relating Systems Thinking and Design (RSD4), 2015 Banff, Canada. Systemic Design Research Network.

SUNSTEIN, C. R. & HASTIE, R. 2015. *Wiser: Getting beyond groupthink to make groups smarter*, Boston, Massachuetts, Harvard Business Press.

TAYSOM, E. & CRILLY, N. 2017. Resilience in Sociotechnical Systems: The Perspectives of Multiple Stakeholders. *She Ji: The Journal of Design, Economics, and Innovation*, 3, 165-182.

TESSELAAR, R., CORNELISSEN, W. & ENGELBERTINK, J. 2013. Renewable energy: access and impact. *IOB Evaluations (Netherlands) eng no. 376*.

TETLOCK, P. E. & GARDNER, D. 2016. *Superforecasting: The art and science of prediction*, Random House.

TETT, G. 2015. *The silo effect: The peril of expertise and the promise of breaking down barriers*, Simon and Schuster.

THACKER, K. S., BARGER, M. & MATTSON, C. A. A global review of end user needs: Establishing the need for adaptable cookstoves. Global Humanitarian Technology Conference (GHTC), 2014 IEEE, 2014. IEEE, 649-658.

THOMPSON, J. D. 1967. *Organizations in action: Social science bases of administrative theory*, New York, McGraw-Hill.

TSCHOCHNER, H. 1954. Konstruieren und gestalten. *Essen: Girardet*.

TVERSKY, A. & KAHNEMAN, D. 1991. Loss aversion in riskless choice: A reference-dependent model. *The quarterly journal of economics*, 106, 1039-1061.

UBELS, J. & JABOBS, F. 2016. Scaling: from simple models to rich strategies. *Explorations*. Rotterdam: PPPLab Food & Water.

UBELS, J. & JACOBS, F. 2018. Shaping successful scaling processes. *Explorations*. Rotterdam: PPPLab Food & Water.

URMEE, T. & GYAMFI, S. 2014. A review of improved Cookstove technologies and programs. *Renewable and Sustainable Energy Reviews*, 33, 625-635.

VAN BEERS, C., KNORRINGA, P. & LELIVELD, A. Frugal Innovation in Africa: Schumpeter revisited. 2013. Discussion paper for the International Workshop 'The (Mis) Fortune of Frugal Innovation', Grenoble, 2829 March.

VAN BOEIJEN, A. G. C., DAALHUIZEN, J. J. & ZIJLSTRA, J. J. M. 2020, rev. ed. *Delft Design Guide: Perspectives-Models-Approaches-Methods*, Amsterdam, BISPublishers.

VAN DER BIJL-BROUWER, M. The power of trust and motivation in a designing social system. Relating Systems Thinking and Design 2017 symposium, 2018. Systemic Design Research Network.

VAN DER KLEIJ, A. 2008. *Comparing contexts. Developing the solar dew technology for Madagascar and Pakistan.* Master thesis. Delft.

VAN ENGELEN, J. & VAN BOMMEL, H. 2020. *Part two: Why managers should learn to cycle*, Cycle to Accelerate.

VAN GILS, S. 2016. *Baby Viewer: An ultrasound device for the African medical world and the Western consumer market.* MSC thesis, Delft University of Technology.

VAN SPRANG, S. 2017. *The design of a charcoal-based cooking stove matching the cooking and food habits in Uganda and Ghana.* MSc thesis, Delft University of Technology.

VAN TULDER, R. & VAN DER ZWART, A. 2005. *International business-society management: Linking corporate responsibility and globalization*, London, Routledge.

VERGANTI, R. 2017. Design Thinkers Think Like Managers. *She Ji: The Journal of Design, Economics, and Innovation*, 3, 100-102.

VERNON, R. 1966. International investment and international trade in the product cycle. *The quarterly journal of economics*, 190-207.

VERNON, R. 1979. The product cycle hypothesis in a new international environment. *Oxford bulletin of economics and statistics*, 41, 255-267.

VON BACH, C. 1881. *Die maschinenelemente*, Cotta.

WÄCHTLER, R. 1967. Beitrag zur Theorie des Entwickelns (Konstruierens). *Feinwerktechnik*, 71, 353-358.

WÄCHTLER, R. 1969. Die Dynamik des Entwickelns (Konstruierens). *Feinwerktechnik*, 73, 329-333.

WAHR, F. & UNDERWOOD, J. Dealing with complexity in education for sustainability-a shared journey for students and teachers in design education. Connected 2010 International Conference on Design Education, 2010. University of New South Wales, 1-6.

WASHBURN, N. T. & HUNSAKER, B. T. 2011. Finding great ideas in emerging markets. *Harvard Business Review*, 89, 115-120.

WEICK, K. E. 2007. The generative properties of richness. *Academy of management journal*, 50, 14.

WHEATLEY, M. 1998. Chaos and the strange attractor of meaning. *Leading organizations: New perspectives for a new era*, 158-165.

WHO 2016. Household Air Pollution and Health. *Fact sheets.*

WIGBOLDUS, S. & BROUWERS, J. 2016. Using a Theory of Scaling to guide decision making: towards a structured approach to support responsible scaling of innovations in the context of agrifood systems. Wageningen University & Research.

WILDEN, A. & HAMMER, R. 1987. *The rules are no game: The strategy of communication*, Routledge.

WÖGERBAUER, H. 1942. *Die Technik des Konstruierens*, Oldenbourg.

WONG, H.-K. 2007. *Cooking in rural China.* MSc, Delft University of Technology.

WOOLDRIDGE, A. 2010. The world turned upside down. *The Economist.*

YIN, R. K. 2017. *Case study research and applications: Design and methods*, Sage publications.

ZESCHKY, M., WIDENMAYER, B. & GASSMANN, O. 2011. Frugal innovation in emerging markets. *Research-Technology Management*, 54, 38-45.

ZHANG, Q. & DOLL, W. J. 2001. The fuzzy front end and success of new product development: a causal model. *European Journal of Innovation Management*, 4, 95-112.

TU Delft

ISBN 978-94-6366-260-4