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Causality and Interpretation: Integrating the Technical and Social Aspects of Design

Ergo Pikas

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Abstract

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Abstract

A number of well-recognized problems, many arising from the inadequate organization of design processes, beset the building design and design management. Remedies have been attempted but no effective solutions have emerged. The root problem could be the prevailing view of incompatibility between the technical, subject to causality, and social, subject to interpretation, standpoints. A way to address this issue is to go back to first principles.

Aristotle provided a first account of the productive act based on two strategies of inquiry: the method of analysis and rhetoric. The discovery of the dual nature of design theorizing by Aristotle gave rise to the hypothesis that a general solution might be provided by a new integrated design concept. The primary aim was thus defined as follows: to develop a comprehensive philosophical and conceptual framework as well as a design model integrating both technical and social phenomena and to use the resulting theory to develop better design and design management practices.

To meet the research aim and select the research methodology, four main research questions were posed: (1) What are the key philosophical ideas relevant to the framing of design conceptualizations? (2) What are the fundamental concepts of ancient design theories (i.e., the method of analysis and rhetoric) in the ancient Greek context and in contemporary contexts? (3) What kind of new design model can be constructed based on these two strategies of inquiry? (4) How does the new model benefit design and design management practices?

Design research methodology was adopted to answer the research questions. The answers to the questions were arrived at through arguments, findings, and constructions: (1) Concerning the philosophical framing, it is argued that pragmatism is more appropriate than positivism or constructivism, as it would permit the synthesis of the technical and social perspectives. (2) The two ancient strategies of inquiry, the method of analysis and rhetoric, help clarify fundamental design concepts. These strategies of inquiry need to be integrated for a more comprehensive conceptualization of designing. (3) For an understanding of the relationships between the fundamental concepts of designing, a new more comprehensive design model was constructed. The new model represents the structure of the design process. (4) With a view to the evaluation of the model and development of support for practice, three case study interventions were carried out. An initial implementation of the new model through instantiations in practice brought significant quantitative and qualitative improvements.

Overall, three contributions to the body of design knowledge are made: the formalization of a new design process model; an elucidation of the intellectual history of the design discipline; and the clarification of core terms, concepts, and their relationships in the context of design.

Keywords Design, design activity, design process, method of analysis, rhetoric, strategies of inquiry, building design, building design management

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Tiivistelmä

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Ergo Pikas

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Kausaliteetti ja tulkinta: suunnittelun teknisten ja sosiaalisten näkökulmien yhdentäminen

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Tiivistelmä

Rakennussuunnittelussa ja sen johtamisessa on lukuisia yleisesti tunnettuja ongelmia, joista monet johtuvat suunnitteluprosessien puutteellisesta organisoinnista. Useita keinoja on kokeiltu, mutta tehokkaita ratkaisuja ei ole näköpiirissä. Keskeisenä pulmana voisi olla vallitseva käsitys teknisen ja sosiaalisen näkökannan yhteensopimattomuudesta; tällöin tekninen viittaa kausaalisuuteen ja sosiaalinen tulkintaan. Yksi tapa lähestyä tätä kysymystä on palata ensimmäisiin periaatteisiin.

Aristoteles oli ensimmäinen, joka esitti näkemyksen tuotannosta. Hänen teoriansa perustui kahteen lähestymistapaan: analyysin menetelmä ja retoriikka. Aristoteleen duaalisen suunnittelun teorian löytäminen johti hypoteesiin, jonka mukaan uusi yhdennetty suunnittelun käsite saattaisi tuottaa yleisen ratkaisun. Tutkimuksen päätavoitteeksi otettiin seuraava: kokonaisvaltaisen filosofisen ja käsitteellisen kehikon ja teknisiä sekä sosiaalisia ilmiöitä yhdistävän suunnittelumallin kehittäminen, ja tästä johtuvan teorian käyttäminen nykyistä parempien suunnittelu- ja suunnittelujohtamistapojen kehittämiseen.

Tutkimustavoitteen operationalisointia ja tutkimusmetodologian valitsemista varten esitettiin neljä pääasiallista tutkimuskysymystä: (1) Mitkä ovat suunnittelun viitekehykselle oleelliset filosofiset ideat? (2) Mitkä ovat antiikin suunnitteluteorioiden (analyysin menetelmä ja retoriikka) perusluonteiset käsitteet antiikin Kreikan ja nykyajan näkökulmasta? (3) Minkälainen uusi suunnittelumalli voidaan luoda näiden kahden lähestymistavan pohjalta? (4) Kuinka tämä uusi malli hyödyttää suunnittelun ja suunnittelujohtamisen käytäntöä?

Tutkimuskysymyksiin vastaamiseksi omaksuttiin suunnittelututkimuksen metodologia. Vastaukset asetettuihin kysymyksiin luotiin argumenttien, löydöksien ja konstruktioiden kautta: (1) Pragmatismin perustellaan olevan positivismia ja konstruktivismia sopivampi filosofinen viitekehys suunnittelulle. (2) Kaksi antiikin lähestymistapaa, analyysin menetelmä ja retoriikka, auttavat selkeyttämään perusluonteisia suunnittelukäsitteitä. Suunnitteluongelmien ja -ratkaisujen sisältäessä vaihtelevassa määrin kausaliteettia ja tulkintaa, nämä lähestymistavat täytyy yhdentää kattavamman suunnittelun käsitteellistämisen aikaansaamiseksi. (3) Uusi kokonaisvaltainen suunnittelumalli luotiin valaisemaan suunnittelun perusluonteisten käsitteiden välisiä suhteita. Uusi malli kuvaa suunnitteluprosessin rakennetta. (4) Kolme tapaustutkimusinterventiota suoritettiin mallin arvioimiseksi sekä sen käytön tukemiseksi. Mallin alustava toimeenpano käytännön toteutuksien muodossa sai aikaan huomattavia määrällisiä ja laadullisia parannuksia.

Kaiken kaikkiaan saa suunnittelututkimuksen ala tämän tutkimuksen myötä kolme tiedonlisää: uuden suunnitteluprosessimallin formalisointi; suunnittelun oppiaineen aatehistorian valaiseminen; sekä suunnitteluun ja sen johtamiseen liittyvien ydintermien, käsitteiden ja näiden välisten suhteiden selkeyttäminen.

Avainsanat Suunnittelu, suunnittelutoiminta, suunnitteluprosessi, analyysin menetelmae, retoriikka, tutkimuksen strategiat, rakennussuunnittelu, suunnittelun johtaminen

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Causality and Interpretation: Integrating the Technical and Social Aspects of Design

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This dissertation was accepted for the defense of the degree of Doctor of Philosophy in Engineering on January 3rd, 2019.

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Defense of the thesis: 13.05.2019, Espoo

Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology and at Aalto University School of Engineering, has not been submitted for doctoral or equivalent academic degree.

Ergo Pikas:

signature

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TALLINNA TEHNIKAÜLIKOOL
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Põhjuslikkus ja tõlgendamine: projekteerimise tehniliste ja sotsiaalsete aspektide sidumine

ERGO PIKAS

Kokkuvõte

Ehitiste projekteerimist ja projekteerimise juhtimist kammitsevad mitmed probleemid, tingitud näiteks puudulikust projekteerimise protsessi korraldamisest. Probleemide lahendamiseks on proovitud mitmeid abinõusid, kuid toimivat lahendust pole tekkinud. Põhiprobleemiks võib olla valitsev seisukoht, et projekteerimise tehniline (keskendub põhjuslikkusele) ja sotsiaane (keskendub tõlgendamisele) vaade on omavahel vastuolus. Selle probleemi lahendamine eeldab tagasiminekut algpõhimõtete juurde.

Aristoteles käsitles esimesena tootlikku tegevust (kavandamist ja realiseerimist) lähtudes kahest uurimisstrateegiast: analüüsi meetod (ehk geomeetriliste probleemide lahendamise metood) ja retoorika (ehk argumenteerimise meetod). Aristotelese kavandamise kahese käsitluse avastamine selles doktoritöös ajendas sõnastama hüpoteesi, et üldine lahendus võiks seisneda kahe erineva käsitluse omavahelises sidumises. Seetõttu püstitati töös järgmine peaeesmärk: välja töötada terviklik filosoofiline ja kontseptuaalne raamistik, samuti mudel, mis seovad kavandamise tehnilised ja sotsiaalsed nähtused ning kasutada uut teooriat kavandamise ja projekteerimise juhtimise praktika parendamiseks.

Uurimistöö eesmärgile jõudmiseks ja metoodilise raamistiku valimiseks püstitati neli küsimust. (1) Millised filosoofia kontseptsioonid on olulised kavandamise teooria sõnastamiseks? (2) Millised on antiiksete kavandamise teooriate (s.t. analüüsi meetod ja retoorika) peamised kontseptsioonid Vana-Kreeka ja tänapäeva kontekstis? (3) Millise kavandamise uue mudeli saab koostada, võttes aluseks mõlemad uurimisstrateegiad? (4) Kuidas on uus mudel kasulik kavandamise ja projekteerimise juhtimise praktikas?

Töös rakendati küsimustele vastamiseks kavandamise uurimismetodoloogiat. Küsimustele vastati argumentide, järelduste ja konstruktsioonide abil. (1) Filosoofilise raamistiku osas väidetakse, et pragmatism on sobivam kui positivism või konstruktivism, kuna see lubab lõimida omavahel projekteerimise tehnilist ja sotsiaalset vaadet. (2) Kaks antiikset uurimisstrateegiat, analüüsi meetod ja retoorika, aitavad selgitada põhilisi kavandamise kontseptsioone. Kuna projekteerimise probleemid ja lahendused kätkevad erinevas proportsioonis põhjuslikkuse (tehniline vaade) ja tõlgendamise (sotsiaalne vaade) küsimusi, siis tervikliku kavandamise kontseptsiooni koostamiseks peab need uurmisstrateegiad omavahel siduma. (3) Põhikontseptsioonide vaheliste seoste mõistmiseks loodi uus laiaulatuslikum kavandamise mudel. Uus mudel kujutab kavandamise protsessi struktuuri. (4) Mudeli hindamiseks ja praktilise toe väljatöötamiseks viidi läbi

kolm juhtumiuuringut. Uue mudeli esialgne kasutamine praktilistes näidetes tõi kaasa märkimisväärseid kvantitatiivseid ja kvalitatiivseid parendusi.

Kokkuvõtlikult antakse töös järgmised kolm panust kavandamise teadmistesse: uue kavandamise protsessi mudeli sõnastus, kavandamise valdkonna intellektuaalse ajaloo selgitamine ning põhiliste mõistete, kontseptsioonide ja nende seoste selgitamine kavandamise ja projekteerimise juhtimise kontekstis.

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Most of all, I am indebted to my family, Karin Ventsel, Nete Pikas and Nolan Pikas for their unconditional support and being my source of inspiration. I want to thank my mother and father for giving me their personal values, and unconditional love. I am also grateful to my brother and many friends. I could not have completed this journey without all of you.

Helsinki, 2018
Ergo Pikas

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Author's Contribution

The research described in this doctoral dissertation, monograph was performed by the author with support and guidance from the supervisors. In chapters 1, 2, 4, 5, 7 and 8, the author provided the ideas and wrote the chapters. Some of the results have been published in journal and conference articles, in which the author has been, in many cases, the leading author. In parts one and three of the sub-section 3.1.3, the doctoral student gained ideas from the co-authored paper published in the Journal of Construction Engineering and Management (Koskela et al. 2018). However, in this dissertation, new ideas and material are introduced. Also, the second case study in section 6.2, was initially carried out by two doctoral students, including the author. The other doctoral student helped to prepare the simulation models for energy analysis. The author provided the ideas and wrote the case study.

As being the advisor of this dissertation, I hereby confirm that the author's contribution is valid and as presented in this section.

Prof. Lauri Koskela

The beginning is the most important part of the work.

Plato

1. Introduction

This chapter provides a general introduction to the thesis (section 1.1): stating the motivation for the research and defining the problem; describing the general problems faced in the design and construction of buildings; and identifying needs and knowledge gaps in the industry and academic research design. In section 1.2, research aims and questions are stated, with motivation drawn from the abundance of problems arising in the design of buildings and design management processes. Section 1.3 sets out the scope of the research and underlying assumptions. Section 1.4 outlines the research approach. Finally, section 1.5 provides a summary of the thesis structure.

1.1 Motivation and Problem Definition

The planning, design, construction, and operation/maintenance of the built environment are beset with long-standing problems. In this section, problems involved in the design of buildings and the management of design processes are described to shed light on needs and knowledge gaps. These problems together provide the primary motivation for this research.

1.1.1 The Pervasiveness of Problems

The pervasiveness of problems in the design of buildings and management of building design processes is widely recognized. These problems range from the aesthetic to the technical and managerial and can be any combination of these. Typical concerns regarding the poor performance of the construction industry include the following:

- Construction processes are wasteful, as only 10 – 30 % of the total time expended is value-adding (Horman and Kenley 2005; Jongeling and Olofsson 2007).
- Productivity growth is low in the construction industry, when compared to that in other industries (Teicholz et al. 2001).

- Construction projects face frequent cost/time overruns (Chan and Kumaraswamy 1996), leading to legal disputes, especially in the supply chain (Sacks and Harel 2006).
- Construction supply chains are highly fragmented (Howell et al. 2010).
- The construction industry as a whole is underdeveloped when it comes to the adoption and implementation of new technologies (Koskela and Kazi 2003; Samuelson 2002; Tas and Irlayici 2007).

The following three vignettes typify the failures that frequently arise in the design of buildings and management of design processes. Problems related to the structural and sustainable design of buildings and the management of design and engineering processes, in particular, are highlighted.

Failing Engineering Design of Buildings

Building designers carry a great responsibility: the decisions of designers directly affect all subsequent stages of construction project delivery, including the construction, use and remodeling/demolition of a building. However, according to Love and Li (2000) and Love et al. (2008), poor designs are the cause of up to 70% of the total amount of rework. Design errors have been considered the primary “contributor to building and infrastructure failures as well as project time and cost overruns” (Lopez et al. 2010).

Similar findings for different geographic regions have been reported in two more recent studies (Agarwal et al. 2012; Behikhalu and Dawam 2014): around 50% of all failures in construction projects were directly attributable to design faults, while deficiencies in construction caused about 25-40%, and defective materials and products accounted for about 10%. The overloading of structures caused only about 4% of structural failures (Agarwal et al. 2012). Design errors have also led to numerous fatal accidents and injuries during the construction and operation of buildings (Chapman 1998; Feld and Carper 1997).

According to Lopez et al. (2010), “practitioners have found it increasingly difficult to learn from their mistakes, particularly with regard to the prevention, identification and/or containment of design errors.” A variety of causes has been proposed for these errors. Some researchers have even started to debate whether all of the problems can be eliminated, as there is no one-size-fits-all solution to the challenges of building design (Chong and Low 2006).

As for countermeasures, the proposal made by Lopez et al. (2010) seems one of the most comprehensive. They argue that adherence to proper organizational and project management practices and the provision of an environment for individuals to learn from their mistakes have the greatest potential to improve design practices. As a significant insight, it recognizes the importance of managing design processes. Specifically, it supports the need to improve the management and organization of building design organizations/projects and processes.

Failing Sustainable Design of Buildings

It has been reported that buildings consume up to 40% of energy produced and account for up to 36% of CO_2 emissions in the European Union (Eichhammer et al. 2009). Attempts to improve energy efficiency and reduce CO_2 emissions have, however, been facing many challenges, including (Kalamees et al. 2012; Kalamees et al. 2014; Kõiv et al. 2014; Pikas et al. 2014; Pikas et al. 2015; Ryghaug and Sørensen 2009; Sunikka-Blank and Galvin 2012):

- energy consumption exceeds the energy rating;
- energy consumption falls below that calculated on the basis of statistical averages;
- low indoor air quality;
- poor construction quality;
- poor designs;
- over-investment; and
- low resident satisfaction.

Studies over the last two decades have reported problems that have been recurring on different scales in different countries across the construction industry. Engdahl (1998) reported that only 34% of all 5,625 ventilation systems studied met minimum performance requirements prescribed by local legislation in Sweden. Van Ginkel and Hasselaar (2003) looked at indoor air quality problems and resident's complaints in Dutch buildings. Ryghaug (2009) considered energy efficiency problems and related regulations in Norway. As shown by Kalamees et al. (2014) and Kõiv et al. (2014) in studies carried out between 2012 and 2014, the same problems were still evident in Estonia, including poor indoor air quality, failure to achieve expected energy savings, and dissatisfied residents. Hence, it appears that not much had changed over the last two decades.

Poor Design Management

The need to manage and coordinate design processes more effectively has been recognized for some time in the fields of industrial product development and mechanical engineering, and later in architecture and the design of buildings in general (Farr 1966; Ballard and Koskela 1998; Emmitt 2010). The need to manage design project delivery arose at first from the division of master builder into separate dedicated disciplines, the increased body of design knowledge being beyond the capacity of any individual to possess (Bucciarelli 1994; Kranakis 1997; Reed 2009). The increased body of design knowledge and concomitant specialization have escalated the complexity of construction project delivery, necessitating more thorough collaboration, cooperation, coordination, and management of design and engineering processes through more effective communication (Kleinsmann 2006).

However, design management has not been up to the task. According to Lopez et al. (2010), one way to address the countless problems encountered in the building design processes is to develop proper organizational and project management practices that also make it possible to learn from mistakes. Instead, design managers tend to focus on managing projects, deliverables, tasks, resources, and contracts, that is, on the formal (technical) aspects of project delivery, and pay less attention to managing people, the environment and processes, that is, the dynamic (changing) features of project delivery (Koskela and Kagioglou 2006; Rekola et al. 2012).

Summary and Discussion
Different studies in three different disciplines repeatedly refer to the same design failures, which have, for example, led to rework, fatal accidents, injuries, and poor performance (poor energy efficiency and indoor air quality, over investment, etc.), demonstrating a low level of progress. What is the reason for these many failures? If we wish to solve these problems in the construction industry, they must be addressed at the root level. That is, design research must move away from a piece-meal (reductionist) approach to a more holistic one to answer the question whether the causes for these problems are spread across many domains, or there are significant root-level causes that could be remedied through more concentrated efforts. For example, Love (2000) argued that questions related to philosophical framing, the design process and the object must be addressed when developing a design theory.

1.1.2 Gaps in Design Research

Design as an academic discipline emerged around the 1960s. Since then, the term design has become widely used to refer to the design discipline, design activity, or design task (problems and solutions). From the beginning, there were two schools of thought: a technical (formal and rational) perspective and an argumentative one. The former is concerned with the causality of the design object and activity, the latter with the interpretation of human purposes and interactions. For example, engineering design (Gregory 1966; Hubka and Eder 1996) is representative of the technical perspective; human-centered design (Norman 2005; Steen 2012) and participatory design (Sanders and Stappers 2008) of argumentative design conceptualizations. The following sub-sections address questions related to the history and philosophy of the productive act, design theory, and sources of inspiration for design theorizing.

History and Philosophy of Productive Act
The technical view of the productive act (including design, production, and management) has predominated since the industrial revolution, when the division of work, specialization, and standardization (interchangeable parts) became the chief principles underlying planning, designing, and the guiding of human efforts towards expected outputs (Ford 1926; Pikas et al. 2017; Smith 1776). These changes were partly triggered by changing economic, social and intellectual forces in the 18th century. Together with the founding of new academic institutions, they led to the establishment of different engineering disciplines and later, subordinate disciplines (Channell 2009). Different scientific engineering disciplines emerged mainly in areas where the basic sciences (e.g., physics, chemistry, and earth sciences) were well-understood (Channell 2009). Traditional and artisan methods of 'trial-and-error' to produce artefacts were considered inefficient. It was recognized that the improvement of the predictability of engineered solutions required the application of scientific knowledge (*episteme*) for design/engineering purposes (Rankine 1872).

Central to this new vision and a guiding principle of the industrial revolution was the dichotomy between theory and practice, thinking and doing, which had roots in Cartesianism (Coyne and Snodgrass 1993). Aristotle had, of course, also made a distinction between thinking and doing (theory and practice), but for him, this distinction merely provided conceptual clarity (Aristotle 2001).

Since then, there have been significant advances in manufacturing, culminating in the development of mass production in the early 20th century by Henry Ford (1926). The allocation of scarce resources became the core idea of economics (Samuelson 1997). The same principles and focus also gained a foothold in construction project delivery (Moder and Phillips 1964), where the development of an optimal plan based on optimal tasks became the core principle of project management (Koskela et al. 2014). The focus of the mainstream project management shifted to the design and preparation of centralized plans imposed on the world (Taylor 1914) - a vision heavily influenced by Cartesian philosophy (Johnston and Brennan 1996).

This view was also applied to design as an academic discipline. The technical conceptualization of the design object or activity was the prevailing view for the first few decades following the 1960s. The technical view, however, soon encountered criticism from its early pioneers. Alternative approaches to these design and design management conceptualizations were proposed in the 1970s (Rittel and Webber 1973) and the early 1990s (Emmitt and Ruikar 2013), to be known as the social conceptualization of design and design management. Today, design as a social process is broadly recognized in the design domain (Love 2003). Design as an interpretative/argumentative phenomenon is described by Bucciarelli (2002):

> Designing is not faithfully represented as simply the art of applied science pursued by an individual at a work station or drafting board. In most cases today, it is the business of groups of individuals who, if they are to be effective, must know how to discuss, deliberate and negotiate with others if their individual proposals and claims are to be taken into account and have meaning.

Which view (technical or social) better addresses the problems summarized in sub-section 1.1.1? This may, however, not be the right question. If these two conceptualizations of design activity emerged as early as the 1960s and 1970s, why are there still so many problems in the design and construction of buildings? These two approaches alone have apparently not helped to solve the problems spread across the different stages of building project delivery.

One primary reason could be the dichotomization of design conceptualizations and the prioritization of either the technical or social perspective. This dichotomy would be in line with general scientific practices in the 20th century, when the positivist and constructivist paradigms of research were the prevailing philosophical views (Bedny and Meister 2014; Fellows and Liu 2009; Losee 2001). According to Buchanan (2009), the first design methods movement was heavily influenced by the positivist research paradigm, the second design methods movement by the constructivist research paradigm (Love 2003). This would explain the dichotomization of design conceptualizations into technical and social camps, as the two philosophical starting points (positivism and constructivism) were and have been considered different and incompatible (Creswell 2013).

Here, it is argued that neither of the two is correct: for a more comprehensive understanding, design needs to be addressed holistically, as the interaction between the technical, the social phenomenon manifested in the object, and subject-oriented human activities. As such, this forms the first knowledge gap, which requires the investigation of philosophical questions for the proper framing of design theorization, to ascertain whether it is possible to create a synthesis of the technical and social phenomena.

Aristotelian Production Science and Design Theorizing

Design scholars, following either the positivist or constructivist approaches, have derived inspiration from different fields to operationalize their design conceptualizations, including mathematics, logic, philosophy, and practical arts (Buchanan 1985; Gedenryd 1998; Love 2000), to name a few. However, the majority of contemporary design scholars have either neglected or overlooked the works of the ancient Greeks.

Aristotle (384-322 BC) provided a first proper account of the theory of production by distinguishing different human intellectual virtues (Telford 1967). Broadly, Aristotle categorized human knowledge as either theoretical (*episteme*) or practical (*phronesis* and *techne*) (Aristotle 2001; Richard 2008). The difference between the two types of virtues, theoretical sciences and the practical together with productive sciences, is that *episteme* is the study of universal and invariable things (underlying regularities), while *techne*, the science of production, is the study of the particular and probable things (Richard 2008).

As part of the first proper account of the theory of production, Aristotle described the nature of design and making. Aristotle's remark in the Nicomachean Ethics is instructive and provides a way to conceptualize design (Aristotle 2001):

> For the person who deliberates seems to investigate and analyze in the way described as though he were analyzing a geometrical construction [...]

This describes the affinity between design and the method of analysis (alternatively, the geometric method). The geometrical method was sophisticated and already well-defined at the time of Plato and Aristotle (Hintikka and Remes 1974; Menn 2002; Netz 2003). The method of analysis not only influenced Plato and Aristotle but the entire history of Western thought thereafter (Goldenbaum 2015): the development of rationalism and empiricism and the entire history of the philosophy of science.

Similarly, rhetoric, which was first addressed systematically by Aristotle (2012), also influenced the development of Western thought (Herrick 2015; McKeon 2003; McKeon 1968). For example, Netz (2003) argued that the oratory practices of ancient Greece even influenced the development of deductive practices in geometrical problem-solving. Both strategies of inquiry, the method of analysis and rhetoric, couple thinking with doing, planning with acting, designing with making – each pair of concepts being complementary and inseparable.

Although Simon (1981) and Buchanan (2009) acknowledged that the roots of the strategies of change (design) could be traced back to Aristotle's four causes (Falcon 2015), they did not link design to the Aristotelian concept of productive sciences, the conceptualization of which, however, was influenced by the method of analysis and rhetoric. This shortcoming inspired Koskela to argue that Simon's work was hardly seminal (Koskela 2008):

> [...] the commonly held view of Simon as the seminal contributor to design science is wrong. Aristotle made a similar, sophisticated call for a science of production 2300 years earlier. Unfortunately, it has been forgotten, misunderstood or it has run out of fashion. This is in stark contrast to many other calls of Aristotle, which are now considered seminal.

Thus, another possible reason for poor progress in the field of design, as revealed by a brief look at the history of design theory, is that design research started from scratch in the 1960s, without awareness of the sophisticated seminal theories presented in classical antiquity. Thus, the second gap to be addressed in this thesis is to study what are the key concepts and principles of the method of analysis and rhetoric.

The Method of Analysis and Rhetoric

Since Aristotle's time, geometry had been seen to provide a model for necessary reasoning, and rhetoric a model for plausible reasoning (McKeon 1968). Regarding the method of analysis, Gedenryd (1998), Koskela and Kagioglou (2006), Codinhoto (2013), and Koskela et al. (2014) proposed that the technical conceptualizations of design originate in methods for solving geometrical problems. The importance of geometry cannot be overestimated. For example, Hestenes (2006) argued that "[...] without geometry, there is no science".

Gedenryd (1998) studied the relationship between Euclid's description of the method of analysis and design in 1998 but was superficial regarding the identification of the essential features of the method of analysis. Koskela and Kagioglou (2006) proposed that the Aristotelian productive sciences, which Aristotle based on the method of analysis, are fundamental to the conceptualization of productive inquiry. Indeed, as Koskela and Kagioglou argued (Koskela and Kagioglou 2006):

> [...] despite that the ancient method of analysis (geometry) and its understanding was lost, including also the precise contents of analysis and synthesis, the conception of (engineering) design as rational, necessary reasoning has persisted throughout the history, to be the common assumption in contemporary (engineering) design theories.

More design scholars have been keen to propose rhetoric as the underlying model for the social conceptualization of design. Numerous researchers have studied the relationship between rhetoric and design (Ballard and Koskela 2013; Buchanan 1985; Halstrøm 2017; Kaufer and Butler 2013; Stumpf 2001). Ballard and Koskela (2013) state that "the conceptualization of these scholars is best represented in the view that rhetoric is design limited to words and design is rhetoric with an unlimited palette." Design has been considered the deliberative, epideictic, or judicial genres of rhetoric (Buchanan 2001; Halstrøm 2017; Koskela et al. 2018). In rhetorical discourse, designers follow different lines of argumentation and pull knowledge from special and familiar places, similarly to the use of *topoi* in classical rhetoric (Burton 1996; Halstrøm 2016; Halstrøm 2017).

Thus, the proposition that the method of analysis and rhetoric independently underlie design conceptualization is not new to the design community. However, only Koskela and Ballard (2013) have studied the relationship between the two strategies of inquiry as the underlying model for design conceptualization. That is, to the best knowledge of the author, only one scholarly contribution has attempted to synthesize the two strategies of inquiry, proposing the idea of two pillars of design (Koskela and Ballard 2013).

The synthesis of these two ancient strategies of inquiry to conceptualize design activity is expected to provide a more holistic theory of design and the design process, contributing to the operationalization of the technical and social conceptualizations of design activity; facilitating the change from how things are to how things ought to be (Simon 1981), communicating meaning (Krippendorff 1985), or communicating the intention of a designer (Buchanan 1985). A few contemporary examples of the synthesis of these two perspectives already exist. For example, contemporary formulations of activity theory (Bedny and Harris 2005; Bedny and Karwowski 2004; Engeström et al. 1999) describe human activity as an activity system consisting of an object and subject-oriented activities influenced by contextual factors (culture, history, division of work, etc.).

The third gap to be addressed in this thesis is whether the two seminal theories of human inquiry, the method of analysis and rhetoric, can be combined to create a comprehensive design model.

Design Theory: Descriptive and Prescriptive

If the lack of a proper theory for the design of buildings has hindered the development of the field, then it should be asked what the role of a 'good' theory of design is. Traditional perspectives on the function of scientific theory include: to describe, explain and predict the behavior of phenomena (Losee 2001). In addition to these functions, production theories (including the theory of design) must also prescribe an action (de Figueiredo and da Cunha 2007).

Design scholars have, generally, acknowledged the importance of theory in design (Dixon 1987; Le Masson et al. 2017; Love 2000). Reich et al. (2012), for example, argued that the development of design methods ought to rely on proven theories. Cavallucci (2014) adds that design theories must be relevant to practice. Badke-Schaub and Eris (2013) describe a proper design theory as the following:

> [...] a body of knowledge which provides an understanding of the principles, practices and procedures of design. That knowledge leads to hypotheses on how designers should work, and such hypotheses provide the basis for the prescriptive part of design methodology.

Frequently, design theories are instantiated within the design model(s) (Wynn and Clarkson 2017). However, models focusing exclusively on description or prescription can have limitations that hinder their usefulness. Zeiler and Savanovic (2009) proposed in their conceptualization to combine the descriptive and prescriptive functions of models, retaining the strengths of both approaches.

In the present research, design theories are considered in the context of production science, meaning that a proper conceptual framework and theory would facilitate the following (Weisbrod and Kroll 2017): the development of design practices; understanding of different methods; different perspectives on problems that were previously unclear; and change of practices.

Furthermore, a comprehensive theoretical foundation would aid the comparison of different conceptualizations of design, while up to now the theoretical foundation of design science has been somewhat superficial, as suggested by Koskela (2008):

> In contrast to explanatory natural and social sciences, the normative design (or productive) sciences have suffered from a long neglect. Even if the interest towards design sciences has increased in the last fifty years, they have remained too fragmented and atheoretical to have a real impact. In consequence, the many application areas of design science, such as design, construction and maintenance of the built environment, are still suffering from the underdevelopment of this science.

Similarly, Kannengiesser and Gero (2009) argued that it is the lack of theory that has led to an insufficient understanding of design, while Clark and Fujimoto (1991) argued that it is the lack of the overall coherence of the product development system, meaning the poor embodiment and implementation of practices. However, as the same problems have been recurring over several decades, the position of Kannengiesser and Gero (2009) seems more defensible. It is not just the poor implementation and quality of various systems and elements of design and construction but also inadequate theory that has hindered the development of better practices. Thus, this forms the fourth research area, an acknowledgement of the importance of developing theory-based practices.

1.1.3 Identification of Knowledge Gaps

The overall motivation for this research stems from unresolved problems in construction practice and the limitations of design research. Here, based on the discussions in sub-section 1.1.2, a summary is presented of the practical needs and academic knowledge gaps around which this research is organized.

1. **The philosophical framing of design conceptualizations:**

Contemporary design conceptualizations tend, often implicitly, to dichotomize the theorization of design and designing as either a technical or social phenomenon. Design scholars leaning towards the technical conceptualization of design tend to be influenced by the positivist research paradigm, design scholars leaning towards the social conceptualization of design by the constructivist research paradigm. However, reliance on the positivist or constructivist paradigm alone has failed to yield solutions to those recurring problems in building design and the management of design processes. Therefore, the knowledge gap to be investigated is whether the two views can be synthesized. If they can, then what is the proper philosophical framing and how can it be accomplished? These questions make it paramount to return to the first principles.

2. **The ancient strategies of inquiry:**
   Various approaches have inspired contemporary design conceptualizations. However, as was illustrated in sub-section 1.1.2, conceptualizations of design and making were proposed as early as the time of Plato and Aristotle. If the method of analysis and rhetoric inspired Plato and Aristotle, it is essential to understand if these two are still relevant and can be used to conceptualize design activity. With few exceptions, contemporary conceptualizations have had a tendency not to consider these origins. Thus, the second significant gap and subject being addressed in this study is the identification of the fundamental concepts and principles of the two ancient strategies of inquiry within both their original and contemporary contexts and a determination of whether they might justifiably underlie the development of a theory of design.
3. **The ancient strategies of inquiry as underlying concepts for a new design model construction:**
   If the two ancient strategies of inquiry are still relevant, can a new design model be synthesized, integrating the technical and social views of design activity? Thus, to address the third knowledge gap, a new more comprehensive conceptualization of design is proposed, instantiated as a design model.
4. **Improving Design and Design Management Practices:**
   Building design and the management of design processes encounter frequent failures. Despite the remedies proposed by different design and design management scholars, the same problems still recur. Thus, to fill the last knowledge gap, which was also the starting point for this thesis, better practices are developed based on more comprehensive conceptualizations of design activity to achieve qualitative and quantitative improvements.

1.2 Research Aim, Objectives and Main Questions

Based on the identified problems, needs, and knowledge gaps, the main aim of this research is twofold:

> **(1) to develop a comprehensive philosophical and conceptual framework as well as a design model integrating both technical and social phenomena; (2) and to use the resulting theory to develop better design and design management practices.**

As such, this research is divided into two major parts:

1. In the descriptive part, the goal is to develop an appropriate understanding of design activity by synthesizing the technical and social views of design, operationalized by ancient methods of inquiry. The final output of this part is philosophical and conceptual frameworks for describing the design activity as a series of situated object- and subject-oriented mental and external actions. This part fills the first two knowledge gaps.
2. In the prescriptive part, the goal is to develop a new design model to improve design and design management practices based on part 1, at the same time, evaluating the practical relevance of new conceptualizations and the proposed model. This fills the third and fourth knowledge gaps.

To meet the stated aims and evaluate the success of the research against knowledge gaps, the following measurable objectives are proposed as criteria:

1. To develop a proper philosophical framing for design conceptualizations.
2. To identify key concepts of the two ancient strategies of inquiry within both ancient and contemporary contexts.
3. To develop a new design model by integrating the technical and social conceptions of design activity.
4. To develop methods relevant to design practice and to improve design and design management processes.

Four research questions are proposed to operationalize and meet research aims and objectives:

1. What are the key philosophical ideas relevant to the framing of design conceptualizations?
2. What are the fundamental concepts of the method of analysis and rhetoric in both the ancient Greek and contemporary contexts?
3. What kind of new design model can be constructed based on these two strategies of inquiry?
4. How does the new model benefit design and design management practices?

These different research aspects are presented in **Table 1**, where the needs of the industry and the knowledge gaps in academia are connected with the research aim, objectives, questions, and finally, expected outputs. The table should be read from left to right. Each research area must deliver the expected research outputs, here named as a philosophical framework, conceptual framework, new design model, or theory-driven practices for the first, second, third, and fourth research areas, respectively.

Table 1. Summary of framework governing research.

<table>
<tr><th>Needs / Knowledge Gap</th><th>Research Aim</th><th>Research Objective</th><th>Research Question</th><th>Outputs</th></tr>
<tr><td>The philosophical framing of design conceptualizations</td><td rowspan="3">(1) to develop a comprehensive philosophical and conceptual framework as well as a design model integrating both technical and social phenomena</td><td>To develop a proper philosophical framing for design conceptualizations</td><td>What are the key philosophical ideas relevant to the framing of design conceptualizations</td><td>Philosophical Framework</td></tr>
<tr><td>The ancient strategies of inquiry</td><td>To identify key concepts of the two ancient strategies of inquiry within both ancient and contemporary contexts</td><td>What are the fundamental concepts of the method of analysis and rhetoric in both the ancient Greek and contemporary contexts</td><td>Conceptual Framework for Design and Designing</td></tr>
<tr><td>The ancient strategies of inquiry as underlying concepts for a new design model construction</td><td>To develop a new design model by integrating the technical and social conceptions of design activity</td><td>What kind of new design model can be constructed based on these two strategies of inquiry</td><td>New Design Model</td></tr>
<tr><td>Improving Design and Design Management Practices</td><td>(2) and to use the resulting theory to develop better design and design management practices</td><td>To develop methods relevant to design practice and to improve design and design management processes</td><td>How does the new model benefit design and design management practices</td><td>Theory-Driven Practices</td></tr>
</table>

1.3 Research Scope and Starting Points

The present research focuses largely on the philosophical framing and theoretical conceptualization of design activity and the development of a new design model based on ancient strategies of inquiry. This requires going back to first principles, the original conceptualizations of productive sciences and the fundamental strategies of inquiry, to operationalize the different perspectives of design conceptualization.

These new philosophical and theoretical frameworks together with the new design model are expected to help improve building design and design management practices. Design activity will be conceptualized as a processual phenomenon (from the perspective of process metaphysics). The main unit of analysis in this research is the design activity, including the mental and external object and subject-oriented activities.

The conceptual developments of the design activity are included in the new design model to achieve the objectives of this research. When treating the numerous problems in the construction industry, the emphasis is on the development of theory-informed design and design management practices. The following, for example, fall outside the scope of this thesis: an analysis of services, product and organization architectures, and optimization methods for the design process, such as the design structure matrix.

Based on the preliminary literature review, three starting points are assumed to be given. First, the dichotomization of design conceptualizations into the technical and social is one of the reasons for ineffective practices and academic approaches. Here, it is assumed that the two are complementary and can be used together to derive a more comprehensive design model. For example, the activity theory integrates the object and subject-oriented activities influenced by contextual factors (Bedny and Harris 2005; Bedny and Karwowski 2004; Engeström et al. 1999). This leads to a more holistic approach to the conceptualization of design activity. This approach is also consistent with some contemporary conceptualizations, such as the two pillars of design conceptualization by Koskela and Ballard (2013).

The second starting point is that when the methods of analysis and rhetoric are considered as generic strategies of inquiry, these can be transformed and adapted to other domains, design in particular. As evident from the earlier sections of this chapter that this view is supported by some contemporary scholars.

The third starting point is that design is an activity of a human agent, and thus, any theorization about designing can be understood only in a human context. This assumption is also supported by several design scholars (Bedny and Meister 2014; Cash and Kreye 2017; Love 2000).

1.4 Research Approach

Within the domain of productive sciences, purely descriptive research is argued not to be suitable for solving issues that have practical relevance (de Figueiredo and da Cunha 2007). Therefore, the design research methodology (DRM) has been adopted. DRM was proposed by Blessing and Chakrabarti (2009) as an alternative to the 'design science' based research methodology. This methodology is used to develop scientifically grounded solutions that can solve problems with practical relevance (Blessing and Chakrabarti 2009).

In Chapter 2, a detailed description and justification of the research methodology, including a description of stages followed to identify the problem, develop solutions, and evaluate practical as well as conceptual outcomes, are provided. In total, seven steps have been followed in this thesis:

(1) Identification of problems related to design and design management practices and academic approaches, identification of knowledge gaps, and establishment of research project aims, objectives and questions.
(2) Analyses of the philosophical ideas relevant to the framing of the design conceptualizations.
(3) Study of the ancient methods of inquiry and their connection to contemporary design conceptualizations.
(4) Construction of a new design model.
(5) Evaluation of the usefulness of the new model based on its implementation in design and design management practices.
(6) General evaluation and discussion of the thesis outputs and outcomes, as well as a conceptual evaluation of the model against contemporary conceptions of design.
(7) Summary of conclusions.

1.5 Thesis Structure

Overall, this thesis is organized into eight chapters as follows:

- **Chapter 2:** Presentation of the research methodology and justification of the selection of research methods and case studies.
- **Chapter 3:** Presentation of the philosophical and historical background of the productive sciences and proposal of philosophical ideas to be used to frame design conceptualizations.
- **Chapter 4:** First, the characteristics of a theory and the elements and concepts of the design theory are addressed to establish the requirements for the model construction. Second, an investigation of the connection between contemporary design conceptualizations and the two ancient strategies of inquiry is considered. Third, it is studied whether the features of the ancient strategies of inquiry have similar or analogous counterparts in current design theorizations. Finally, a summary of the fundamental concepts of the two ancient strategies of inquiry is presented.
- **Chapter 5:** Construction of a new design model in a step-wise manner based on the new insights gained in Chapters 3 and 4.
- **Chapter 6:** Presentation of the results of the application of the new design model in three case studies, with the objective of evaluating the practical utility of the model.
- **Chapter 7:** An overall evaluation and discussion of the research outputs and outcomes. Discussion of the contributions, validity and implications to design and design management theories and practices.
- **Chapter 8:** Conclusion. Main findings and answers to research questions. Limitations of the research and directions for the future research.

In addition to the main chapters, the thesis contains appendices for supplementary materials.

Understanding a question is half an answer.

Socrates

2. Research Design

In this chapter, the overall research design, the philosophical and methodological approaches, and the selection, combination, and justification of research methods for data collection, analysis, and evaluation are described. Section 2.1 provides a short overview of the philosophical frame of this study. Section 2.2 elaborates on the previously introduced research objectives and questions and establishes success criteria for industrial and academic evaluation. Section 2.3 describes the research stages based on the Design Research Methodology framework. Section 2.4 introduces the three case studies and explains the strategies employed for data gathering, analysis, and interpretation. Finally, section 2.5 offers a chapter summary.

2.1 Research Philosophy

As every research is subject to assumptions and beliefs (Saunders et al. 2009), the philosophical position taken must be described. A research paradigm, a concept explicated by Kuhn (1962), refers to the framework that ties together different elements of research. A variety of paradigms can be distinguished on the basis of three dimensions (Bryman 2003): ontology, epistemology, and methodology. An ontology defines assumptions about reality, epistemology about knowledge, and methodology is concerned with the strategy of research for designing, selecting, and connecting methods (Creswell 2012). Within the context of design, positivism (Hubka and Eder 1996; Simon 1981), constructivism (Buchanan 1992; Buchanan 2009; Cross 2007) and pragmatism (Dalsgaard 2014; March 1984; Melles 2008; Rylander 2012) have been identified as the relevant research paradigms.

The choice of paradigm in this thesis is justified on the basis of the subject matter: design activity and design management. Design as a human activity is the conception of an artefact, a thing that does not exist yet. Design operates in a specific situation, subject to a diversity of views and interpretations. The use of descriptive approaches, such as the positivist or constructivist paradigm, is not suitable for answering the question of how things ought to be (Creswell 2012; Creswell 2013; de Figueiredo and da Cunha 2007). Instead, research in the design, and more generally, in the productive sciences, should have a practical relevance (Holmström et al. 2009). Thus, such research should be prescriptive or contain a prescriptive element.

In this study, pragmatism was chosen as the philosophical frame. The pragmatist paradigm was first proposed by Charles Sanders Peirce (1839–1914) (Cherryholmes 1992; Dalsgaard 2014; Rorty 1990). While positivism is concerned with objective descriptions of reality, knowledge, and methodology and constructivism with subjective descriptions, pragmatism is concerned with the production of practical consequences (Losee 2001). In the pragmatist philosophy, theories are instruments linked to experience and practice, and there is no preference for any one system of theory or reality (Creswell 2013). Pragmatism could perhaps be the only paradigm to support the aim of this study: to develop a comprehensive conceptual framework as well as a design model, which can then be used to develop design and design management practices that are more effective. Thus, the selection of the research methodology in the following sections is motivated by the considerations stated here, and the chosen methodology must contain both descriptive and prescriptive elements (Voordijk 2009).

2.2 Research Objectives, Questions and Success Criteria

The needs and knowledge gaps identified in section 1.1 guided the formulation of the research aim, objectives, and questions in section 1.2. In this section, these objectives and questions are considered on more granular level. At the end, academic and industrial success criteria are introduced to facilitate the evaluation of research outputs.

2.2.1 From Needs and Knowledge Gaps to Outputs

Altogether four interconnected focus areas were identified in section 1.2: (1) the philosophical framing of design conceptualizations; (2) fundamental concepts of ancient strategies of inquiry and their relation to contemporary design conceptualizations; (3) the ancient strategies of inquiry as concepts underlying the construction of a new design model; and (4) ineffective design and design management practices. Research areas are organized from the most general to the more specific, from descriptive to prescriptive, from philosophical to methodological and practice-oriented. In the following sub-sections, these four research areas are specified in detail and aligned with Love's (2000) philosophical structure for design conceptualizations. Love (2000) proposed a framework and structure based on ten levels of abstraction for positioning the elements and concepts of different design theories relative to each other.

The Philosophical Framing of Design Conceptualizations

The present research was motivated by the recognition that contemporary conceptualizations of design, designing, and design management tend to categorize design as either technical or social phenomenon. However, relying solely on the technical or social conceptualization of design activity has not led to better practices. Hence, poor practices may in fact be due in part to this one-sided conceptualization of design. This dichotomization is partly a result of the reliance on different, incompatible philosophical starting-points, including the positivist and constructivist views of design research. This philosophical consideration also essentially precludes the issue of design "theories and theoretical developments not [being] subjected to sufficient critical epistemological and ontological attention" (Love 2000). The first research objective was thus defined as the development of a proper philosophical framing for the development of design theory. To operationalize the research objective, the first research question was defined as follows:

> **RQ1: What are the key philosophical ideas relevant to the framing of design conceptualizations?**

The answer to this question should produce a philosophical framework, which should then form the basis for the remainder of this research. To answer this question and be able to give consideration to the different aspects of philosophical framing, three sub-questions are proposed. These sub-questions are motivated by the idea that no design conceptualization takes place in a vacuum. A particular view determines the focus of analysis, its content (considered or disregarded features) and expected outcomes. Therefore, the first sub-question addresses the determination of the central concepts in the philosophy of science that are relevant to design conceptualizations. The second sub-question addresses the underlying philosophical assumptions of contemporary productive sciences, including the design, engineering and management sciences. The third sub-question addresses the dominant 20th century research paradigms that design scholars have used to ground research, including the positivist, constructivist and pragmatist paradigms. These are important for understanding why the different productive science disciplines have developed as they have.

> **RQ1.1: What concepts of philosophy are relevant to design conceptualizations?**

> **RQ1.2: How were the different productive science disciplines philosophically grounded at their emergence?**

> **RQ1.3: How have contemporary design conceptualizations been philosophically grounded?**

The Ancient Strategies of Inquiry

Contemporary conceptualizations of design activity have taken inspiration from many different sources, often without thorough justification, for example, from logic, mathematics, cognition, and argumentation (e.g., dialectical and rhetorical) theories. Aristotle was the first to provide a proper account of productive sciences, including the designing and making of objects, by using the method of analysis and rhetoric. However, the majority of contemporary design scholars seem to have failed to consider the Aristotelian productive sciences a potential starting point for design theorization. Thus, in agreement with the design philosophical approach proposed by Love (2000), one aim of this research is to avoid the problem of "theories [being] speculatively proposed" and "some useful theories that would help with the integration of Design Theory [being] ignored, partly because they are 'not invented here', or perhaps because they lie outside what is seen as the province of the study of design." Thus, the second primary objective was the identification of the fundamental concepts of the two ancient strategies of inquiry in both the ancient and contemporary contexts. The second research question was formulated to operationalize this objective:

> **RQ2: What are the fundamental concepts of the method of analysis and rhetoric in both the ancient Greek and contemporary contexts?**

The answer to this question should lead to a conceptual framework which takes concepts and principles from the two different perspectives, conceptualizing design as both a technical and social phenomenon. It is assumed that based on these concepts, principles, and components, a new more comprehensive design model can be constructed. However, to develop a theory of design, it is essential to study the 'anatomy of design theories' (Gregor and Jones 2007), that is, to determine the requirements for a unified theory of design. Furthermore, to justify the claim that many design conceptualizations have neglected historical concepts, the connections between contemporary and the ancient conceptions of design inquiry are investigated. Also, there are two reasons for comparing contemporary conceptualizations of design with the concepts of the two ancient strategies of inquiry before constructing a new design model: the first, to develop a common understanding of the two ancient strategies of inquiry; the second, to align the vocabulary used in the two ancient strategies of inquiry with modern design terminology. Therefore, to answer RQ2 and meet the objective of the second research focus area, the following three sub-questions were introduced:

> **RQ2.1: What are the key characteristics and elements of a unified theory of design?**

> **RQ2.2: How are the two ancient methods of inquiry connected to contemporary design conceptualizations and how do these conceptualizations compare to the two ancient strategies of inquiry?**

> **RQ 2.3: What are the fundamental concepts of the two ancient methods of inquiry?**

The Ancient Strategies of Inquiry as Underlying Methods for New Design Model Development

The method of analysis and rhetoric as strategies of inquiry were already established methods of inquiry during the time of Plato and Aristotle, and have been used with more or less success by some contemporary design scholars. However, contemporary scholars have tended to use either the former or the latter alone. Thus, the objective of this research area is to determine what kind of more comprehensive design model embodying both the technical and social conceptions of design activity can be developed by integrating these two strategies of inquiry. The third research question was defined as follows:

RQ3: What kind of new design model can be constructed based on the two strategies of inquiry?

The answer to this question should manifest itself in a new design model. After the construction of a new design model, it is also important to evaluate the new model against contemporary design conceptualizations. Thus, to answer RQ3 and meet the objective, the main question was divided into two sub-questions. These two sub-questions are intended to frame the development of the conceptual design model and its evaluation, that is, to justify the need for a new design model and show its usefulness.

RQ3.1: How will a new model based on the two ancient methods of inquiry be synthesized?

RQ3.2: How does the new model compare to contemporary design conceptualizations?

Improving Design and Design Management Practices
The starting point for this research area was the identification of frequent failures in practices in design, the sustainable design of buildings, and design management. With the additional aim of solving practical problems, the objective of this research area is to develop instantiations relevant to design practices and to improve design and design management processes. The fourth research question was stated as follows:

RQ4: How does the new model benefit design and design management practices?

The new model should lead to better design and design management practices, have qualitative effects (e.g., transparency of design processes) and quantitative effects (e.g., increased profit). To this end, it is essential to understand what kind of methods and instantiations can be created based on the new conceptual design model and what kind of benefits these bring. This would be, in essence, the empirical evaluation of the new proposed design model. Accordingly, two sub-questions were defined. However, the answers to these questions will not be exhaustive but consist of examples.

RQ4.1: What kind of methods can be instantiated based on the new conceptual design model?

RQ4.2: How will the new conceptualization of design activity when instantiated help to improve design activity and design management?

2.2.2 Success criteria

The outputs of the four research areas should fulfill the aim of this research, meet industrial and academic needs, and resolve knowledge gaps. Based on the stated research objectives and questions, the following measurable criteria were defined to evaluate the success of the proposed new design model in industrial and academic contexts.

Industrial Success Criteria

Conceptual framework for design and designing: This should deliver a better understanding of the fundamental concepts relevant to design and design management practices by providing a methodological description of design activity (strategies, principles, and design procedures) according to the conceptualization of design as a technical and social phenomenon.

New design model: This should provide a more comprehensive overview of the design activity in practice. The proposed model should also be operational and usable in practice.

Theory-driven practices: A better understanding of the design activity should support the development of better practices, methods, and techniques, resulting in better design and design management processes and outputs/outcomes. Thus, the approach developed should lead to qualitative and quantitative improvements in design and design management processes.

Academic Success Criteria

Philosophical Framework: The philosophical framing of perspectives, assumptions and principles should provide new insights into the proper philosophical approach of the design activity and its related concepts: metaphysics, ontology, epistemology, and methodology (methods).

Conceptual Framework: This is a description of the design activity which should provide new insights into design strategies, principles, and procedures.

New design model: This should explain the dynamics of the design process and prescribe the design activities that a designer carries out when designing.

Theory-driven practices: While descriptive models set standards that elements of the design process should satisfy, theory-driven practices should embody a set of prescriptive norms appropriate to each design practice.

2.2.3 Organization of the Thesis

The remainder of this thesis is organized around the research areas and related objectives, questions, and outputs. Chapter 3 addresses the philosophical framing of the design conceptualizations. Chapter 4 considers the two ancient methods of inquiry, their historical relevance, and their connections with contemporary design conceptualizations. Chapter 5 proposes a new design model based on the two ancient methods of inquiry. Chapter 6 summarizes the case studies. Chapter 7 evaluates the research outputs against academic and industrial success criteria defined in sub-section 2.2.2. Chapter 8 provides a discussion and summarizes the conclusions of this study. **Table 2** presents the organization of thesis according research questions and outputs.

Table 2. Organization of thesis according research questions and outputs.

Research Question and Sub-Questions	Location of Outputs
RQ1: What are the key philosophical ideas relevant to the framing of design conceptualizations?	**Chapter 3**
RQ1.1: What concepts of philosophy are relevant to design conceptualizations?	Chapter 3, Section 3.1
RQ1.2: How were the different productive science disciplines philosophically grounded at their emergence?	Chapter 3, Section 3.2
RQ1.3: How have contemporary design conceptualizations been philosophically grounded?	Chapter 3, Section 3.3
RQ2: What are the fundamental concepts of the method of analysis and rhetoric in both the ancient Greek and contemporary contexts?	**Chapter 4**
RQ2.1: What are the key characteristics and elements of a unified theory of design?	Chapter 4, Sections 4.1 and 4.4
RQ2.2: How are the two ancient methods of inquiry connected to contemporary design conceptualizations and how do these conceptualizations compare to the two ancient strategies of inquiry?	Chapter 4, Sections 4.2 and 4.3.4
RQ 2.3: What are the fundamental concepts of the two ancient methods of inquiry?	Chapter 4, Section 4.3
RQ3: What kind of new design model can be constructed based on the two strategies of inquiry?	**Chapters 5 and 7**
RQ3.1: How will a new model based on the two ancient methods of inquiry be synthesized?	Chapter 5, Sections 5.1-5.5
RQ3.2: How does the new model compare to contemporary design conceptualizations?	Chapter 7, Sections 7.1
RQ4: How does the new model benefit design and design management practices?	**Chapters 6 and 7**
RQ4.1: What kind of methods can be instantiated based on the new conceptual design model?	Chapter 6, Sections 6.1-6.3
RQ4.2: How will the new conceptualization of design activity when instantiated help to improve design activity and design management?	Chapter 6, Section 6.4 and Chapter 7, Section 7.2.1

2.3 Research Methodology

This section outlines the research methodology: general concepts, stages, and methods. In the construction industry, the majority of research tends to be descriptive (Azhar et al. 2009; Fellows and Liu 2009), with a focus on investigating and describing design and managerial problems either from the technical or social science perspective. In descriptive studies, the researcher is primarily an observer, rather than a solver of problems and agent of change. This type of research has been criticized for producing results that have marginal value to practice (Holmström et al. 2009).

Conversely, the prescriptive approach can lead to better design and management practices, more effective field procedures, and improved levels of productivity (Azhar et al. 2009). Unlike the researcher in a descriptive study, the researcher in a prescriptive study takes an active role in the research project.

Despite the fact that prescriptive research methodologies have become accepted practice, especially in other disciplines, design science research (DSR) and action research (AR) are rarely considered when investigating and solving design and managerial problems in the construction industry (Koskela 2008).

DSR and AR, in fact, make it possible for a researcher to become involved with practitioners in studying their work and becoming co-agents of change (Azhar et al. 2009).

DSR originated in the science of the artificial (Simon 1981), which according to Lukka (2003) "focuses on developing and evaluating innovative artifacts, intended to solve real-world problems and to make a contribution to the theory of the discipline in which it is applied." March and Smith (1995) propose four types of artifacts that can be developed and evaluated in DSR: constructs, models, methods, and instantiations (**Table 3**). Here, the focus is on developing constructs, models, and instantiations.

Table 3. DSR artefacts as defined by March and Smith (1995).

Artifact	Definition
Constructs	Constructs make up the vocabulary of a domain. They constitute a conceptualization used to describe problems within the domain and to specify their solutions.
Model	A model is a set of propositions or statements expressing relationships among constructs. In design, models represent situations as problem and solution statements.
Method	A method is a set of steps (an algorithm or guideline) used to perform a task. Methods are based on a set of underlying constructs (language) and a representation (model) of the solution space.
Instantiation	An instantiation is a realization of an artifact in its environment, that is, the implementation(s) of constructs, models, and methods, demonstrating the feasibility of the conceptual elements that the solution contains.

The present research implements the design research methodology (DRM) proposed by Blessing and Chakrabarti (2009). It is an alternative to the constructive research approach (Lukka 2003) and design science research (DSR) (Hevner and Chatterjee 2010; Hevner 2007; Iivari and Venable 2009; Kuechler and Vaishnavi 2011).

Also DRM originated in the 'science of the artificial' (Simon 1996), which Blessing and Chakrabarti (2009) defined as follows: "[...] design research integrates [...] two main strands of research: the development of *understanding* and the development of *support*. [Two strands] should, therefore, be considered together to achieve the overall aim of design research: to make the design more effective and efficient, to enable design practice to develop more successful products." The iterative process of using qualitative and quantitative data to increase understanding of phenomena is focused on the development of both theoretical supports (e.g., knowledge and theory) and practical supports (e.g., tools and methods). Thus, the implementation of this framework should enable the researcher to offer both descriptive and prescriptive contributions to design and design management theory and practice.

The DRM process followed by the present research is divided into four stages (**Figure 1**): problem clarification (Chapters 1 and 2); descriptive study I (Chapters 3 and 4), prescriptive study (Chapter 5), and descriptive study II (Chapters 6 and 7). The first stage is concerned with the development of the governing framework, including research aims, objectives, questions, and methodology for connecting research activities with expected outputs. The second stage, descriptive study I, is focused on the development of the philosophical and conceptual frameworks. The third stage, the prescriptive study, involves the construction of a new design model. The last stage, descriptive study II, focuses on the instantiation of conceptual frameworks and models in three case studies and an evaluation of whether the success criteria were fulfilled.

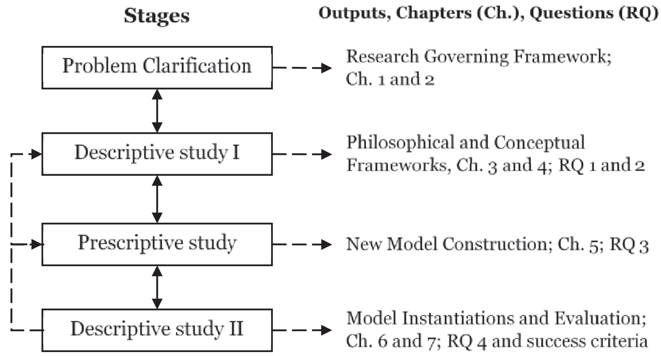


Figure 1. DRM based research stages, adapted from Blessing and Chakrabarti (2009).

2.3.1 Problem Clarification

The first stage, research problem clarification, is addressed in Chapters 1 and 2. The first two chapters develop the research framework, including industrial and academic knowledge gaps, aims, problems, objectives, and the theoretical focus of the research. A preliminary literature review is presented and case studies provided to frame the problem (Koskela et al. 2014; Pikas et al. 2015; Pikas et al. 2015; Pikas et al. 2016): to explore the problem space, develop the framework governing the research, and develop a research methodology to connect outputs.

2.3.2 Descriptive study I

Descriptive study I is divided into two parts, the philosophical and methodological framing and the grounding of design conceptualizations. While much of the focus of this research is on the philosophical and theoretical conceptualization of design activity and the development of a new design model, descriptive study I focuses primarily on a literature review. The integrative literature review approach (Torraco 2005) directs the review, critique, and synthesis of representative literature towards the development of new philosophical and methodological perspectives. The first part of this stage looks at the philosophical ideas relevant to design conceptualizations. The primary results of the first part, addressing the first research question, can be found in Chapters 3 and 5. The objective is to develop a proper philosophical framing for design conceptualizations. The primary results of the second part of this stage, addressing the second research question, can be found in Chapters 4 and 5. The objective is to identify the fundamental concepts of the two ancient strategies of inquiry in both ancient and contemporary contexts, to clarify the methodological questions involved in conceptualizing design activity as a technical and social phenomenon.

2.3.3 Prescriptive study

As was argued earlier, when investigating problems in productive sciences (design and making), the use of methodologies addressing only how things are does not suffice to answer the question of how things ought to be. In the prescriptive study stage, the primary focus is on the construction of a new design model by integrating the technical and social conceptions of design activity (Chapter 5). The philosophical and methodological concepts addressed in the previous stage form a starting point for the construction process.

2.3.4 Descriptive study II

Descriptive study II is also divided into two parts. The first part consists of an evaluation of practical utility through the implementation of the new conceptual model in three case studies (Chapter 6). The evaluation of research results is conducted from a user point of view (Blessing and Chakrabarti 2009): determining if there is any improvement in design and design management practices, i.e., whether the proposed models have practical relevance and support the achievement of qualitative and quantitative improvements. The benefit of using the case study research method is that it makes it possible to study the phenomenon in its natural setting, using the questions of *why*, *what* and *how* (Voss et al. 2002; Yin 2013). The second part provides a general evaluation of research outcomes (Chapter 7). The model developed is evaluated against other contemporary design conceptualizations and models and practical and academic success criteria defined in sub-section 2.2.2.

2.4 Empirical Research

Although the first three central research questions can be addressed through an extensive study of existing literature, the last central research question requires empirical evaluation. It was essential to focus on industrial needs and practices from the start of this research project to ensure results have a practical value.

This section describes the methods used for the empirical study in the last stage, descriptive study II. The case study method was adopted to study design and design management practices and to develop support for their improvement. Case studies are empirical descriptions of particular instances of a phenomenon that are typically based on a variety of data sources (Eisenhardt and Graebner 2007). Yin (2013) defined case research as “a study that investigates a contemporary phenomenon (the ‘case’) in depth and its real-world context, mainly when the boundaries between phenomenon and context may not be evident.” The principal phenomena addressed in this research are design activities, i.e., the mental and external actions of designers when designing. Complementary phenomena investigated in this research are design management practices.

Case studies can be used for different purposes, including exploration, theory building and testing, and theory extension and refinement. Cases can be historical or contemporary descriptions of recent events (Voss et al. 2002). Generally, in case studies, theories are developed inductively, using replication logic (Eisenhardt and Graebner 2007). Case study research reliability and validity can be described using the dimensions of construct validity, internal validity, external validity, and reliability (Voss et al. 2002). In this study, however, case research was not used for theory building, but for research clarification, iterative development of the instantiations of the conceptual model, and evaluation of the fulfillment of industrial success criteria.

The first case study, which involves participatory action research addressing the early stages of design in the development of a new warehouse concept, demonstrates the usefulness of the new model and its ability to prescribe the design activity and its management. The case published in Pikas et al. (2016) is used as a reference, and a re-interpretation of the design phases and steps based on the new model is proposed. The purpose is to understand how a common design framework and model support design and design management practices. The focus is on the argumentative perspective of design activity.

The second case, based on a reinterpretation of a retrospective case study conducted by Pikas et al. (2015), is concerned with energy and cost efficient building design. The objective is to study the methodological issues connected with the conceptual design of energy and cost efficient buildings and to describe design activities at each step and the use of design methods and tools. This case study will also address the importance of studying the sensitivity of energy and cost estimation modeling assumptions. Thus, the focus is on the technical aspect of design activity.

The third case study involves participatory action research with elements of design science research. The author of this thesis not only designed artefacts for practical use but also participated in the development of new practices. Action research strategy is focused on the implementation and evaluation of existing solutions to practical problems in an organizational context and on suggestions for future improvements (Denscombe 2014; Iivari and Venable 2009). Thus, action research requires involving and being involved with practitioners to change social practices. According to Susman and Evered (1978), action research has five general phases: diagnosing, action planning, action taking, evaluating, and specifying learning. In the third case study, a focus group interview and an ERP (enterprise resource planning) database analysis were used to evaluate the impact of practical interventions.

2.4.1 Focus Group Interview

Blessing and Chakrabarti (2009) defined the focus groups as "…group interviews that focus on a specific topic. The group dynamics can enhance the overall outcome of the interview, but may have a negative effect on the contribution of some participants, depending on the person, the topic, and the differences in the status of the participants". Similarly, Saunders et al. (2009) described focus groups as a particular case of a group interview in which topics are clearly defined and collaboratively discussed. The task of the researcher is to facilitate the involvement, control the discussion flow and capture the collaborative discussion about the given topics.

According to May (2011), a focus group interview can provide substantial insights and present additional results. Focus group interviews can be combined with the results obtained in individual surveys and interviews about the same issues. As actions and opinions of others affect the participants, group interviews are useful for achieving consensus. On the other hand, this is also its limitation as criticized by Bertrand et al. (1992). Moreover, the generalizability of group interviews is subject to debate as a small number of participants may not represent the characteristics of a target population.

In the third case study in Chapter 6, the outcomes of the research are evaluated through the focus group interview method. The objective is to understand what worked and not, and what kind of effects the users have noticed. Thus, a focus group interview is used as a method for local evaluation.

2.4.2 Selection of Case Studies

For the present research, three cases studies were chosen. In this section, basic case study facts and the methods used are summarized. The first case study considers results at the early stages of design when developing a new warehouse concept, focusing on the social and interpretative dimensions of the design process. This participatory action research, carried out in the second half of 2015, used observations, document analysis, and group work research methods.

The second case involves the conceptual design of energy and cost efficient buildings based on a reinterpretation of a retrospective case study conducted by Pikas et al. (2015). This study, initially carried out by two doctoral students, including the author of this thesis, and supervised by two professors, makes it possible to evaluate the methodological questions connected with the conceptual design of energy and cost efficient buildings from a technical perspective. It also helps to illustrate the importance of analyzing the sensitivity of energy and cost estimation modeling assumptions.

The third case makes it possible to evaluate the improvement of design and design management practices based on the new model and designed interventions. This case study focused primarily on the integration of two different perspectives, the technical and social views of design and design management processes. It was longitudinal, carried out by the author of this thesis together with the members of a design office. The study, which ran from the beginning of 2016 until the end of 2017, followed the action research cycle. Two iterations were carried out, and several methods were used to collect, analyze, and synthesize data. The general characteristics of the three case studies are summarized in **Table 4**.

Table 4. General characteristics of the three case study projects.

Description	Case Study I	Case Study II	Case Study III
Purpose	To evaluate the ability of the new design model to prescribe design activities in the early stages of design	To evaluate the conceptual design of energy efficient buildings and illustrate the importance of modelling simulation assumptions	To evaluate the impact of the new design model to improve design and design management practices
Nature of case study	Social conceptualization of design	Technical conceptualization of design	Integration of technical and social conceptualizations of design
Type of a case study	Participatory action research	Retrospective	Longitudinal and participatory action research with design science research elements
Number of people involved	One researcher and the members of a design office	Two researchers (and two supervisors)	One researcher and the members of a design office
Research Project Life-Time	The second half of 2015	The initial study was carried out in 2015 and the second in 2017	From spring 2016 until the end of 2017
Iterations	No iterations	No iterations	Two iterations
Research Methods	Observations, project documents, and group work	Secondary data collection, experimental case study implementing methods retrospectively	Surveys, quantitative macro analysis, observations, group work, and focus groups

2.5 Chapter Summary

In this chapter, theoretical and practical considerations involved in critical methodological choices were addressed. Research objectives, questions, and success criteria narrowing the scope of the research and helping to organize it were detailed. A general outline of the research, based on the Design Research Methodology, linked to the different parts of this study, was described. Finally, the organization, choice of methods, and general characteristics of the three case studies were discussed. Overall, the development of the research design and methodology was inspired by a need to include a prescriptive element.

As far as laws of mathematics refer to reality, they are not certain, as far as they are certain, they do not refer to reality.

Albert Einstein

3. Philosophical Framing of Design

In this chapter, the intent is to highlight the importance of a philosophical framing of the problems and present ideas for a design conceptualization. De Vries (1993) argued that one way to understand design theories is to study their philosophical dispositions, i.e., the knowledge claims, strategies and methods of inquiry that are used. Similarly, the use of the philosophy of science to conceptualize design was recently proposed by Crilly (2010): "[…] philosophy of science can be expected to yield valuable contributions for design theory".

This chapter is divided into four sections. Section 3.1 describes the basic philosophical ideas relevant to design. Section 3.2 describes the emergence of the different disciplines of the productive sciences and their underlying assumptions. In section 3.3, the prevailing 20th century research paradigms that have influenced design conceptualizations are described. In section 3.4, a summary is provided.

3.1 Fundamental Concepts in the Philosophy of Science

Theories are developed on the basis of specific paradigms (Kuhn 1962) which govern the focus of analysis, the selection of features to be investigated, and expected outcomes. The paradigm governing design is generally known as the design paradigm (Stumpf 2001), which describes the viewpoints, assumptions, and prescriptions underlying design research. The study of these different aspects is also referred to as design methodology (Cross 1984): "the study of principles, practices, and procedures of design".

According to Love (2000), the concepts of the philosophy of science relevant to design conceptualizations include ontology, epistemology, and questions related to the processes (methodologies and methods) and objects of design. Koskela and Kagioglou (2005) add to this list the metaphysics of production and management. These and other related concepts are addressed in the following sub-sections.

3.1.1 Basic Terms in the Philosophy of Science

The philosophy of science is a broad field of study dealing with the systematic investigation of ideas and issues such as logic, ethics, metaphysics, ontology, epistemology, axiology and the history of philosophy (Encyclopedia 2014). In the context of design, an understanding of epistemological assumptions is crucial. Nonetheless, one cannot neglect metaphysics, ontology, and axiology, as design is also governed by assumptions regarding reality and values.

The term paradigm has several interpretations, but the contemporary understanding was proposed by Kuhn (1962). Kuhn studied the history of science and argued in 'The Structure of Scientific Revolutions' that scientific activity is guided by a particular paradigm. The Merriam-Webster Online dictionary defines paradigm as "a philosophical and theoretical framework of a scientific school or discipline within which theories, laws, and generalizations and the experiments performed in support of them are formulated; broadly: a philosophical or theoretical framework of any kind" (Dictionary 2018). Paradigm has also been defined as a "cluster of beliefs and dictates which for scientists in a particular discipline influence what should be studied, how research should be done, how results should be interpreted, and so on" (Bryman 2003).

In this work, a paradigm is considered a framework that ties together the following elements: assumptions, values, and practices about what knowledge is, what is knowable, and how we can go about gaining knowledge. Hence, a paradigm is the principle for gluing together three sub-systems (Creswell 2013): ontology, epistemology, and methodology. The paradigm also determines what falls outside the boundaries of a given field of study.

Ontology, a branch of metaphysics, is concerned with beliefs and assumptions about the nature of reality and existence. Epistemology is the study of knowledge (Creswell 2013): the relationship between knowledge and knower; the nature of truth, belief, and justification. Simply put, ontology is about the categorization of things or processes, and epistemology is about the relationship between the researcher (or designer) and reality (Losee 2001).

Methodology, often used interchangeably with the term method, is considered a set of strategies, principles, and practices for selecting, designing and connecting methods for systematically developing new knowledge (Creswell 2012). It describes how the researcher connects methods to expected outputs. A method is a particular technique or tool used to collect, transform, decompose, analyze, synthesize, and evaluate information (McKeon 1966).

3.1.2 Metaphysics and Ontology

There is a difference between the 'old' and 'new' metaphysics. For the ancient and medieval philosophers, metaphysics was the science of the nature of being, the problem of universals, and the nature of substance (van Inwagen 2018). The contemporary understanding of metaphysics is a complicated matter, and there is no commonly agreed definition of what metaphysics is (van Inwagen 2018).

However, it is not the intent of this study to provide a comprehensive understanding of metaphysics; rather, it is concerned with how metaphysics can help to understand the essence of the productive sciences.

Metaphysical Problem of Things and Processes

Since the pre-Socratic period of philosophy, metaphysics has been concerned with the dichotomy of being or becoming, or if the focus is on things or processes, atemporal or temporal things (Roochnik 2004). The so-called 'thing-metaphysics' is focused on 'objectivity' and the discovery of what is necessary; i.e., concerned with certainty and ahistorical questions. 'Process metaphysics' is focused on holistic, historical, and contextual approaches and acknowledgment of uncertainty (Roochnik 2004).

In the context of production and management sciences, Koskela and Kagioglou (2005) argued that production and management sciences should be categorized and perceived based on process metaphysics. They contended that mainstream production and management sciences are mostly informed by the thing-oriented view of the world and that this has led to deficient conceptualizations of management sciences (Koskela and Kagioglou 2006):

> Management based on thing metaphysics is characterized by a centralized, designated subject, carrying out intermittently managerial acts on the things and entities that exist in production, for getting the task done. In contrast, management based on process metaphysics allows for a ubiquitous subject, carrying out continuous acts of management on the productive processes or other, related processes. The objective is to maintain a fit between different aspects and parts of the situation.

Due to the predominance of thing-centered metaphysics in Western production and management, two significant problems have emerged (Koskela and Kagioglou 2006):

- **conceptual loss:** inability to recognize processual phenomena such as continuous improvement; and
- **explanatory loss:** the miscategorization of a processual phenomenon as a thing-based phenomenon, e.g., seeing production solely as input-output transformation.

Koskela and Kagioglou (2005) described the dependencies between the different levels of abstraction involved in the theorization of production (see **Figure 2**). At the top is the understanding of the world driven by the metaphysical assumptions of reality, the basis for establishing concepts and principles and developing methods and practices for acting in the world. This is in agreement with what Stumpf (2001) proposed: prescriptive practices, subject to irregularities and contextual forces in design activities, are developed based on idealized descriptive concepts relevant to design theorization.

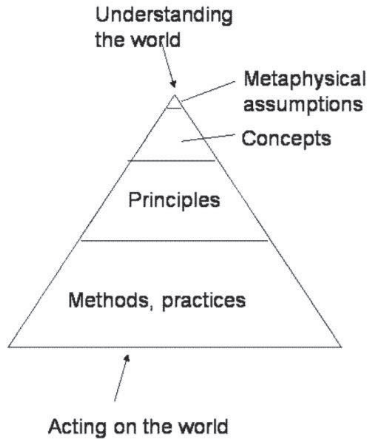


Figure 2. The metaphysical assumptions about theories, principles, methods, and practices (Koskela and Kagioglou 2005).

Although designing is considered a process, studies in design sciences have attempted to categorize design activity from the perspective of thing-metaphysics. For example, when Sim and Duffy (2003) considered product and management-focused perspectives for design activity description and categorization, they described their approach to design activity as knowledge level ontology, i.e., the input and output of design knowledge represented by a symbol structure. Other examples of thing-based design conceptualizations include the science of the artificial by Simon (1981) and the axiomatic design concept by Suh (2001). These theories make either the object of design or the structure of the design activity the primary focus of design theory. Thus, these approaches conceptualize design activity as either the study of objects or the application of formal methods.

However, from the perspective of process metaphysics, design activity is embodied within the situated mental and external actions of a designer. Design activity as a structure and its outputs emerge from self-regulated interactions at the level of design actions and operations (Bedny and Meister 2014; Bedny and Harris 2005). Situated mental and external actions within the domain of process metaphysics always have a temporal dimension and a person assigned to it. A few examples of such conceptualizations of human activity include the situated action, situated cognition, mangle of practice, and communication constituted organization (Pickering 1993; Suchman 1987; Taylor 1999; Winograd and Flores 1986).

In summary, a metaphysical problem is a question about what is more fundamental, things or processes, structures or change. Choosing one or another perspective determines the focus of design theory. In the present research, design is conceptualized as the situated mental and external subject- and object-oriented actions and operations of the designer.

The Ontological Problem of Subjects and Objects

Metaphysics brings to the fore the issues of ontology (Hofweber 2004), the categorization of things, and the split between the mind and body (and environment) (Goldhagen 2017; Van Gelder 1998). In essence, it deals with the following question (Robinson 2017): "what is the relationship between mental properties and physical properties?".

The earliest discussion of the fundamental categories of things can be traced back to the ancient Greek philosophers Plato and Aristotle (Robinson 2017). In all, three broad approaches to ontology have been proposed, including monism, dualism, and pluralism (Van Gelder 1998). Monism asserts the unity of existence, dualism the existence of two fundamental categories of existence, and pluralism the existence of many categories of existence. That is, it deals with the question of whether the mental and the physical – mind and body – are the same things, two different kinds of things, or many kinds of things.

According to monism, there is only one reality. However, the issue of human 'consciousness' has been the main challenge for materialist monism (Van Gelder 1998). Materialist approaches, such as behaviorism, functionalism, mind-brain identity theory, and the computational theory of mind hold that mental states are just the physical states of the brain (Robinson 2017). For example, the information processing view proposed by Simon (1981), amounting to a 'representationalist' view of the mind-reality correspondence (Clancey 1993), assumes that brains, like computers, are symbol processors.

In Cartesian dualism, things and processes are divided into two fundamental kinds or categories (Robinson 2017). This is an underlying assumption of theories addressing design cognition, i.e., the mental and external representations developed by designers (see, for example, Eastman (2001)). Furthermore, Coyne and Snodgrass (1993) argued that the assumptions of the 'transparent mind', the separation of subject and object and the primacy of the individual, have led to the development of formal, rational studies of design dedicated to 'objectification'.

To overcome the dualist split between the mind and the world, Popper introduced the idea of three worlds to describe the different levels of reality. The three worlds include (Popper 2014): World 1 - which consists of physical and material objects, events, and processes (objective); World 2 – which consists of mental events, processes, and predispositions (subjective); and World 3 – which consists of theories, knowledge, and problems (objective products of human thought). The three-world theory of ontology describes the interactions between the pairs of worlds. Popper managed to reconstruct the notion of objective knowledge and fallible and sharable ideas in World 3, which is subject to criticism and empirical tests. Popper classified World 2, which involves personal beliefs and knowledge, as subjective (Popper 2014).

In the context of modelling theory, Hestenes (2006) proposed an interpretation of the mental world, conceptual world, and physical world and the connections between them (see **Figure 3**). He defined subjective mental models as something encoded in neural networks (Hestenes 2006):

> [...] are private constructions in the mind of an individual. They can be elevated to conceptual models by encoding model structure in symbols that activate the individual's mental model and corresponding mental models in other minds. Just as Modeling Theory characterizes science as construction and use of shared conceptual models, I propose to characterize cognition as construction and manipulation of private mental models.

Hestenes (2006) proposed the following definition for objective conceptual models encoded in symbol systems such as computer models:

> [...] a representation of structure in a material system, which may be real or imaginary. The possible types of structures include systemic structure (composition, environment and connections), geometric structure (position and configuration), object structure (properties of the parts), interaction structure (properties of (causal) links), and temporal (event) structure (temporal change in structure of the system).

Hestenes (2006) described the material system as follows:

> In a material system, the objects are material things [...]. A material system can be classified as physical, chemical or biological, depending on relations and properties attributed to the objects.

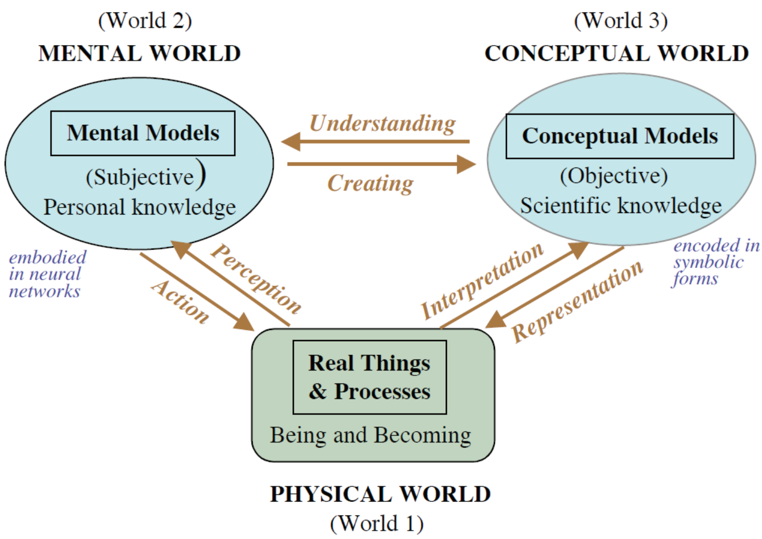


Figure 3. Relationships between the three worlds by Hestenes (2006).

The pluralist ontology proposed by Popper is based, further, on the idea that things are more fundamental than processes. As depicted in **Figure 3** and explained by Hestenes (2006), the structures of mental models, conceptual models, and physical things are considered central, while the processes for transitioning between the different structures are less vital.

Popper's division of the world into three domains is a useful idea in the context of design for many reasons. For example, Gero and Kannengiesser (2004) used the three worlds to study design activity from the perspective of product focus.

At the beginning of a design inquiry, designers have their own personal framing of the design task and process. Through the individual and collective development of design models/artefacts, individual mental models are externalized and shared. Models developed can have a variety of purposes, including the development of shared understanding.

In summary, the study of properties, structures, and relationships in either the mental or physical domain is the focus of thing-metaphysics, while the study of mental and external actions and operations is the focus of process metaphysics. The pluralist ontology proposes a third type of reality, the conceptual world of human ideas, mediating between individual mental models and material systems and subject to criticism and empirical tests.

3.1.3 Epistemology

According to the Merriam-Webster Online Dictionary, the term epistemology has its roots in the Greek word *episteme*, from *epistanai*, to understand, know, from *epi-* + *histanai* to cause to stand (Dictionary 2018). Typical questions addressed in an epistemological study include the following (Truncellito 2007): What are the necessary and sufficient conditions of knowledge? What are its sources? What is its structure, and what are its limits? Historically, concepts such as evidence, belief, truth, and justification have been used to answer the three questions (Steup 2005). Classical and contemporary conceptualizations of epistemology are briefly described below. Specifically, classical rationalism and empiricism together with types of reasoning and then contemporary views on epistemology are investigated.

Classical Rationalism and Empiricism

Western philosophy and thought, including the practices of scientific inquiry, originated in ancient Greece (Losee 2001). Two philosophers, Plato and Aristotle, laid the groundwork for the opposition between rationalism and empiricism. In contemporary discussions, these are referred to as classical rationalism and classical empiricism.

Plato established the 'theory of ideas', or 'forms' seen only by the intellect. In Platonic philosophy, the human spirit seeks to know the 'ultimate ideal' of things (Nonaka and Takeuchi 1995). Plato (2002) argued:

> Would not that man do this most perfectly who approaches each thing, so far as possible, with the reason alone, not introducing sight into his reasoning nor dragging in any of the other senses along with his thinking, but who employs pure, absolute reason in his attempt to search out the pure, absolute essence of things, and who removes himself, so far as possible, from eyes and ears, and, in a word, from his whole body, because he feels that its companionship disturbs the soul and hinders it from attaining truth and wisdom? Is not this the man, Simmias, if anyone, to attain to the knowledge of reality?

According to Plato, the physical world is a mere shadow of the perfect world of 'ideas'. Humans should aspire towards perfect and unchanging 'ideas' (Nonaka and Takeuchi 1995). In a practical sense, Platonic philosophy emphasized the application of natural philosophy and mathematics (geometry) to understand the ideal world of "forms" and to use deductive reasoning for demonstration and proof (Losee 2001).

In contrast, Aristotle's philosophy of empiricism emphasized observations as the starting point for inducing general principles, laws, and hypotheses that lead back to reality through deduction (Meos 2011). Aristotle stressed the importance of observation and verification of sensory perception (Nonaka and Takeuchi 1995).

Raphael's famous fresco in the Apostolic Palace in the Vatican shows Plato and Aristotle standing next to each other, one pointing up, the other down – to the world of ideas and material reality, respectively (**Figure 4**). Since then, there has been a never ending debate in the philosophy of science about whether sciences should follow the Platonic or Aristotelian path or some combination of the two (Losee 2001; Meos 1998).

Figure 4. Plato (left) and Aristotle (right) concerned respectively with the Ideal and the Sensible world in Raphael's painting "The School of Athens" (1509).

Several prominent modern and contemporary figures in mathematics and physics, such as Descartes, Newton, Galileo, Hilbert, and Dirac, can be regarded as Platonic. Platonism was fully reintroduced to the West in the 15^{th} century, at the beginning of the Renaissance (Lindberg 2010). Plato had a strong influence on Johannes Kepler (1571-1630), a key figure of the era in science (Lindberg 2010). It was both Plato and Pythagoras that helped lead him to the conviction that elegant mathematical laws must explain the motions of the planets (Di Liscia 2016).

Soon afterward, Galileo Galilei (1564-1642), a contemporary of Kepler, published his works on mechanics and mathematical analysis that supported the same belief. Galileo, however, took a more critical view, setting the foundations for contemporary approaches (Marshall 2011). René Descartes (1596-1650) and Gottfried Wilhelm Leibniz (1646-1716) were less critical and adhered to the Platonic philosophy (Losee 2001).

Aristotelian philosophy also had a strong influence on later scientists and philosophers, leading to the establishment of empiricism. This methodological perspective was developed by Grosseteste, Bacon, Locke, Hume, Newton, Herschel, Jevons, Whewell, and many others (Losee, 1972). In essence, Aristotelian science is about explanation, namely discovering cause and effect relationships.

Thus, Platonic and Aristotelian philosophies persisted through the centuries to the modern period. Nonaka and Takeuchi (1995) summarized the inheritance of Platonic and Aristotelian traditions from the ancient Greek to contemporary epistemology as follows:

> The Platonic and Aristotelian views were inherited through intermediate philosophers by modern epistemology's two mainstreams: the Continental rationalism and the British empiricism.

In summary, the central question of rationalism and empiricism is about the relationship between theory and observation, conceptualization and practice, and the focus of scientific investigation. Plato appealed to deductive reasoning and Aristotle to the complementary frames of inductive and deductive reasoning.

Types of Reasoning in Rationalist and Empirical Sciences

Rationalists suggest that 'true' knowledge is a product of ideal mental processes, and for that, there exists a *priori* knowledge, axioms[1] based on what absolute truth can be deduced (Meos 1998). According to Netz (2003), the ancient Greek practice of the method of analysis shaped the development of deductive methods. Empiricism asserts that there is no a *priori* knowledge, the only source of knowledge being experience. According to this view, things in the world have an objective existence, even if our perceptions of these are illusory (Chalmers 1999; Godfrey-Smith 2009).

Because of these ontological and epistemological differences, rationalism and empiricism also use different methodologies to obtain new knowledge. Nonaka and Takeuchi described the methodological differences as follows (Nonaka and Takeuchi 1995):

> Rationalism argues that knowledge can be attained deductively by appealing to mental constructs such as concepts, laws, or theories. Empiricism, on the other hand, contends that knowledge is derived inductively from particular sensory experiences.

According to Aristotle, scientists should induce an explanatory hypothesis (cause and effect relationship) from the specific cases to be explained and then apply this to other particular cases by deduction (Niiniluoto 1999). Hence, scientific explanation is a transition from knowledge of a fact to knowledge of the reason and the converse. The relationship between theory and observation mediated by the two different types of reasoning is depicted in **Figure 5** (Losee 2001).

[1] Definitions of things that are necessarily true and do not need justification (Netz, 2003).

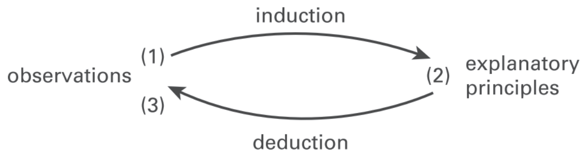


Figure 5. The relationship between theory (explanatory principles) and observation (Losee 2001).

Losee (2001) described the Aristotelian conceptualizations of inductive and deductive steps. The specification of the properties that objects share is an induction of generalizations from sense experience. Aristotle distinguished between two types of induction, both proceeding from particular statements to general statements (Losee 2001): simple enumeration (from particulars to generalizations) and intuitive induction (matter of having the kind of insight that allows one to see that which is "essential" in the data of sense experience). The general form of the first type of inductive reasoning is depicted in **Figure 6**.

a_1 has property P
a_2 „ „ P
a_3 „ „ P
∴ All a's have property P.*

Figure 6. An example of the general form of Aristotle's first type of induction (Losee 2001).

Aristotle had, nevertheless, a relatively simple view of induction, and it remained unchallenged through the Middle Ages and into the 17th century. While Francis Bacon (1620) gave an elaborate description of inductive reasoning (Godfrey-Smith 2009), one of the most well-known descriptions of induction was given by the 18th century Scottish empiricist David Hume, who asked the following (Godfrey-Smith 2009): What reason do we have for thinking that the future will resemble the past?

Since then, more sophisticated treatments of induction have been published, especially in connection with the notion of probability, pioneered by Bayes (1764), Laplace (1812), Boole (1854) (Vickers 2013). For example, Godfrey-Smith (2009) also distinguished between projection and mathematical induction. The former refers to the prediction of a future case based on past cases, while the latter was explained by Netz, whose study of deduction also focused on understanding how the inductive methods were applied in Greek geometrical practices (Netz 2003). As Greek mathematics was concerned with particular and concrete objects, his main conclusion was the following (Netz 2003):

> [...] the entire process is based upon the implicit repeatability of moves in the demonstration. [...] generality is the repeatability of necessity. The awareness of repeatability rests upon the simplification of the mathematical universe [...]

Hestenes (2006) explained this in the context of modelling theory and referred to this idea as an inductive analogy:

> A material analogy relates structure in different material systems or processes. [...] An important case that often goes unnoticed, because it is so subtle and commonplace, is material equivalence of two material objects or systems, whereby they are judged to be the same or identical. I call this an inductive analogy, because it amounts to matching the objects to the same model. I submit that this matching process underlies classical inductive inference, wherein repeated events are attributed to a single mechanism.

In the deductive step, generalizations are used for the deduction of statements about new observations (Losee 2001). For Aristotle, statements are based on the classes of things and the relations of inclusion or exclusion among the classes and can occur as premises or conclusions in deductive arguments. According to Losee (2001): “One of Aristotle’s great achievements was to insist that the validity of an argument is determined solely by the relationship between premises and conclusion”. **Figure 7** depicts an example demonstrating the general form of deductive inference.

PREMISES	All men are mortal Socrates is a man
CONCLUSION	Socrates is mortal

Figure 7. The general form of deduction (Godfrey-Smith 2009).

A study on the cognitive history of deductive approaches by Netz (2003) described the origins and basic concepts of deduction. In his analysis, he employed several concepts from different domains. Netz borrowed the idea of 'formulae' from Homeric studies and applied it (in a modified sense) to Greek geometrical texts; he used the Peircean semiotic classification (indices, icons and symbols) to understand the role of letters in mathematical diagrams; and he took a psychological approach to the idea of 'necessity' in Greek geometrical arguments.

Based on his study, Netz (2003) observed that Greek deductive practices were shaped by two clusters of cognitive tools: the lettered diagrams and the technical, formulaic language. The conclusion was that the most defining feature of Greek mathematics is its form rather than its content. Moreover, deduction is not just about deducing relevant facts, but is also a combination of known facts involving the construction of proofs (Netz 2003):

> Deduction, in fact, is more than just deducing. To do deduction, one must be adept at noticing relevant facts, no less than combining known facts. The eye for the obviously true is no less important than the eye for the obvious result and, as is shown by the intertwining of starting-points and argued assertions, the two eyes act together.

In that sense, Greeks developed the first methods of deduction and, in one way or another, others have formed their ideas based on the texts that these geometers produced (Netz 2003).

At the end of the 19th century and in the beginning of the 20th century, a third type of inference, namely, abduction, took root. Abduction is considered the only type of inference which gives rise to new ideas and is creative (Dong et al. 2012). It was Charles Sanders Peirce who insisted that there is a second type of a probable inference besides induction (Koskela et al. 2018). He referred to it variously in his works as 'hypothesis', 'retroduction' or 'abduction', a term which he coined. In form it was an adaptation of the Aristotelian syllogism (Niiniluoto 1999): if deduction is inference from a major premise, a hypothesis is inference from a minor premise. Hypotheses are of three kinds (Taura and Nagai 2017): a hypothesis can be a 'cause' (for example, a physician diagnosing a patient's disease), an 'explanation', such as a law of nature, and a 'temporary fix' (a working hypothesis, such as auxiliary lines in the method of analysis). The general form of abduction is demonstrated in **Figure 8**.

PREMISES	The surprising fact C is observed; But if A were true, C would be a matter of course.
CONCLUSION	Hence, there is a reason to suspect that A is true.

Figure 8. A general form of abduction (Niiniluoto 1999).

Niiniluoto summarized the differences between the types of reasoning as follows (Niiniluoto 1999): "a typical deduction (syllogism of the first figure) infers a result (conclusion) from a general rule (major premise) and a case (minor premise), induction infers the rule from the case and the result, while hypothesis infers the case from the rule and the result".

In summary, by the beginning of the 20th century, three types of reasoning had been established. Rationalists were the proponents of deductive reasoning, while empiricists emphasized the importance of induction. Abduction was introduced as the only type of inference that can introduce new ideas: cause, explanation and a temporary fix.

Contemporary Views on Rationalism and Empiricism

However, from the 18th century onwards, starting with German philosopher Immanuel Kant, there have been continuous attempts to overcome the limitations of the dualist view developed by Descartes. Kant agreed that the beginning of ideas or knowledge is experience but did not agree that sensory experience is the exclusive source of knowledge (Kant et al. 1998):

> That all our knowledge begins with experience there can be no doubt. But, though all our knowledge begins with experience, it by no means follows that all arises out of experience.

Kant's view has been called 'transcendental idealism' because of his concept of 'thing in itself', which transcends experience. In essence, Kant's view was closer to rationalism than to empiricism. For him, however, knowledge is obtained only when the logical thinking of rationalism and the sensory experience of empiricism are brought together (Nonaka and Takeuchi 1995).

Rejecting the Kantian concept of 'thing in itself', Georg W. F. Hegel argued that both mind and matter could be obtained from the 'Absolute Spirit' through a dialectical process. Nonaka and Takeuchi (1995) described Hegel's dialectical method as follows:

> [...] dialectical is the creation of a synthesis by reconciling thesis and antithesis or rejecting what is not rational and retaining what is rational. For Hegel, knowledge begins with sensory perception, which becomes more subjective and rational through a dialectical purification of the senses, and at last reaches the stage of self-knowledge of the "Absolute Spirit" [...] The self-consciousness of the "Absolute Spirit" is the highest form of knowledge.

Although Hegel attempted to overcome the Cartesian dualism of subject and object with his absolute idealism, his view was, however, also close to rationalism.

Karl Marx proposed another synthesis of rationalism and empiricism by adapting Hegel's dynamic dialectical approach and applying it in emerging social sciences. He contested Hegel's philosophy because it could not explain the dynamic interrelationship between man and his environment. Hegel asserted that new knowledge is a product of the continuous, dialectical interaction of mutual adaptation between the knower (subject) and the known (object) (Nonaka and Takeuchi 1995). For Karl Marx, however, acquiring knowledge was a process of transformation in which the object becomes known by a subject who 'notices' (instead of senses) and acts on these objects. This means that knowledge is acquired through "action", and its truth should be demonstrated in practice (Nonaka and Takeuchi 1995).

According to Nonaka and Takeuchi (1995), 20th century philosophers, including Husserl, Heidegger, Sartre, Merleau-Ponty, Wittgenstein, James, and Dewey, have also challenged dualism and proposed their own conceptions of how knowledge is obtained. Husserl, Heidegger, Sartre, and Merleau-Ponty, as phenomenologists, sought to describe and analyze phenomena, i.e., how the Kantian "things in themselves" appear to human consciousness.

The influential 20th century philosopher Heidegger proposed the concept of Dasein, or being-in-the-world to address Cartesian dualism. It is not merely a spatial inclusion, but a rich being-in (Çüçen 1998): dwelling, communing, being intimate with. As opposed to the knowing self ('*cogito ergo sum*'), Heidegger suggests 'knowing' to be only one mode of being-in-the-world. Heidegger proposed four levels of being in the world (Coyne and Snodgrass 1993): (1) self experiences the situation in wholes, (2) pays attention to the specific (level of meaning), (3) reflects theoretically (with purposeful detachment from the object – the realm of science), and (4) contemplates pure forms (an engagement with bare facts, devoid of feelings - equivalent to Descartes' ontology). In this reformulation, the '*cogito sum*' is only a branch and 'I am in the world' is the root. The first two levels involve experiences of self, and only on the third and fourth levels does the self access the world of ideas. For example, in the social context, this means that one makes sense of self only through interaction with others (Dreyfus 1991).

Two other 20th century movements, analytical philosophy and pragmatism, also focused on the interaction between knowledge and action. Analytical philosophy focused on the language with which people describe a phenomenon (Losee 2001). Ludwig Wittgenstein is one of the central figures connected with its development. In pragmatism, philosophers argued that ideas, theories, and concepts are instruments and can be considered true if they work and help to transform an adverse situation into a preferred one (Rorty 1990).

In summary, since Kant philosophers and scientists have, with some success, made different attempts to overcome the opposition between rationalism and empiricism and between theory and practice. The phenomenologists and pragmatists have come closest to settling the opposition, focusing on the dialogical relation between theory, observation, and a given situation.

3.1.4 Methods and Processes of Inquiry

McKeon (1966), as well as Cellucci (2013), proposed that the origins of methodology and method are in ancient Greece, in the formalization of logic, mathematics (the method of analysis), dialectic, and rhetoric as universal arts. According to McKeon (1966), "common themes of these methods grow out of consideration of deliberation (choice and decision), judgment (or criticism), and demonstration (or exhibiting) as methods of applying reason to the problems of science, art, and action".

According to Cellucci (2013), the word 'method' originates from *methodos*, a compound of *meta* and *hodos*, which means a 'way with'. *Methodos* as a technical term first appeared in Plato's work (McKeon 1966). Before Plato, Parmenides used *hodos* (way), in the same meaning (Cellucci 2013). In Plato's work, *methodos* occurs in the context of a comparison between medicine and rhetoric.

Plato's reference to medicine and rhetoric was also echoed by Aristotle, who stated that "we shall possess the method completely when we shall be in the same condition as in the case of rhetoric, medicine, and other such abilities" (Cellucci 2013). As stated in Chapter 1, Aristotle also compared practical inquiry to the method of analysis. To illustrate what Aristotle may have meant, what Polya writes about the two faces of the method of analysis is useful (Polya 2014):

> Studying the methods of solving problems, we perceive another face of mathematics. Yes, mathematics has two faces; it is the rigorous science of Euclid but it is also something else. Mathematics presented in Euclidean way appears as a systematic, deductive science; but mathematics in the making appears as an experimental, inductive science. Both aspects are as old as the science of the mathematics itself.

Thus, on the one hand, the method is a deductive system for presenting demonstrations and proofs; while on the other, it is the messy process through which these demonstrations and proofs are developed. This resembles the distinction between the 'context of discovery' and the 'context of justification' (Godfrey-Smith 2009; Schickore 2014). In other words, declarative statements about things (factual/propositional knowledge) are developed through the application of procedural knowledge (using methods).

According to McKeon (1966) and Holton (1998), the philosophies framing these methods are either 'analytic' or 'synthetic'. McKeon (1966) described analysis and synthesis as: "[...] analysis on the experience, nature, phenomena, psyches, cultures, or cosmos are the different modes of resolution (the act of analyzing complex matters into simpler ones); and the synthesis of elements, parts, ideas, terms, manifolds – empirical or *a priori* – are different modes of composition". According to McKeon, analysis and synthesis are essentially methods of inquiry and processes of things (McKeon 2003):

> Analysis and synthesis are methods of inquiry and processes of things. Logical statements of analysis and synthesis, therefore, reflect basic metaphysical and epistemological theories.

This passage has a significant meaning, proposing that methods have their origin in analysis and synthesis, and are common in nature (like nuclear fission and fusion) and human inquiry. This view has found application in design conceptualizations. For example, Taura and Nagai (2017) described design inquiry as consisting of two types of processes, analysis, and synthesis:

> Design process is said to be composed of analysis and synthesis. 'To analyze' is to understand the nature of something that already exists by breaking it down into several parts or constituent characteristics. 'To synthesize' is to combine various things that already exist into something that does not yet exist.

Thus, analysis and synthesis are acknowledged processes of inquiry in design. This study employs the definition of inquiry proposed by John Dewey (1925), whose conceptualization of inquiry has captured interest in the design domain (Buchanan 2009; Schön 1984; Schön 1987). Dewey (1925) defined inquiry as:

> [...] the transformation of an indeterminate situation into a unified whole through controlled and directed determinism of its constituent parts and relations.

Thus, a conflicting situation is what triggers the inquiry, a process with an aim to develop new knowledge, resolving doubt, or solve problems. Within design, the discrepancy between the present state and preferred state is what establishes the need and motivation for design inquiry. As such, design is a process of reducing doubt and establishing a state of belief about the proper means to be used to achieve desired consequences.

3.1.5 Section Summary

In this section, philosophical questions involving metaphysics, ontology, epistemology, the primary types of reasoning, inquiry, and methods were addressed. Metaphysics is concerned with the essence of nature, things versus processes, and being versus becoming. Leaning towards the former or the latter means that scientists, as well as designers, seek static or dynamic descriptions of things or processes.

Questions relevant to design conceptualizations arising from ontology, a subfield of metaphysics, include the following. Where do things or processes appear? Are things and processes observer-independent or observer-dependent? It was argued that several seminal examples of design conceptualization have focused on describing design from the perspective of thing-metaphysics, thus, describing the structures (entities, properties, and relationships) of either the design objects or activities (mental and external actions). Contemporary philosophers have attempted to overcome the mind-body dualism by conceptualizing the relation using the notion of the three ontological worlds. This is known as pluralist ontology, which may better explain the complex relations between the designer(s), models, and their objects of design.

Closely related to metaphysics and ontology is epistemology, which is concerned with the creation of knowledge, the relation between theory and practice, and the focus of scientific investigations. Epistemology addresses subjective and objective claims about phenomena. Since ancient times, rationalism and empiricism have influenced the development of different epistemologies. Although nowadays it is considered a mixture of the two views, on a basic level the same opposition between rationalism and empiricism is still evident, as it has been in the philosophy of science for more than 2300 years.

Concepts related to analysis, synthesis, and the theory of inquiry were also addressed. Analysis and synthesis are fundamental ideas consisting of different modes of resolution and composition (proof) and present in both nature and human inquiry. The processes of analysis and synthesis as two distinct types of inquiry or as an integral whole describe the processes involved in developing new knowledge, resolving doubt, or solving problems. According to pragmatism, the perception of a conflicting situation triggers the inquiry.

3.2 History and Emergence of Modern Versions of Productive Sciences

In this section, the emergence of different contemporary disciplines in the productive sciences (design, engineering, and management) and their primary premises are discussed. Although the origins of the productive sciences can be traced back to ancient Greece and Aristotle, contemporary forms of the productive sciences emerged in the early period of the industrial revolution, largely without connections to these origins. The development of the productive sciences was influenced by many different factors belonging to a period beginning before and including the Enlightenment (Channell 2009). The Enlightenment began in the natural sciences (mainly physics) and centered on reason, reductionism, and the application of the scientific method (Losee 2001).

3.2.1 History of Engineering Sciences

The term engineering was first used in the book *La science des ingenieurs* by Bernard Forest de Bélidor (1734). The first engineering school 'École Polytechnique' was founded in 1794 by Lazare Carnot (1753 –1823, a French politician, engineer, and mathematician) and Gaspard Monge (1746 –1818, mathematician and inventor of descriptive geometry) during the French Revolution for training military and civil engineers. The school represented the recognition that these two branches of engineering rested on the same principles, namely the application of scientific knowledge (Channell 2009; Fourcy 1828).

Later, a Scottish civil engineer, physicist, and mathematician William John Macquorn Rankine (1820–1872), working at the University of Glasgow, proposed and developed an autonomous branch of knowledge, which he labeled 'engineering science'. The purpose was to bring together the practical observations and experiences of the properties of materials with the natural and theoretical laws governing the action of machines and structures, and treating them as a science (Rankine 1872). Rankine, as well as the first French engineering school, gave precedence to theoretical knowledge over productive and practical knowledge, meaning that engineering starts with scientific principles, from which conclusions can then be deduced.

Robert Henry Thurston, the first Professor of Mechanical Engineering at Stevens Institute of Technology in the US, argued that instead of applying scientific laws, systematic methods of science must be applied to bring science and experiments together (Channell 2009). This view is evident in an address he published in 1875 (Thurston 1875):

> This is an address to a graduating class of the Stevens Institute of Technology, by the Professor of Mechanical Engineering. Prof. Thurston, in the first place, recalls to the minds of the young engineers the rare educational advantages they have enjoyed at the Institute: very full instruction in mathematics and physics; in modern languages; the English language and literature; principles of engineering, and the practice of the arts connected therewith. So far, the students have been working at the foundation; the superstructure they must build by their own efforts. The professor exhorts them to be wide-awake, observant, conscientious, true to their clients, progressive, radical in theory but conservative in practice, and diligent in study.

Kranakis (1997), who studied the different trajectories of the evolution of bridge engineering practices in 19th century France and America, explains how in France, engineering evolved in an environment which was hierarchically structured (theory, engineering design, and experience) and where theoretical-deductive methodology predominated, rooted in a highly mathematical approach.

The opposite was true in America, where knowledge of theory, engineering design, and experience were related horizontally, and the objective was to bring these three together, taking an empirical approach. American bridge engineers used the empirical-inductive methodology, meaning that engineering was always seen to take place in a specific context driving the discussion on the particular and probable (Kranakis 1997). Thus, it can be inferred that the French took a top-down approach, whereas Americans took a bottom-up approach, reflecting rational and empirical philosophies, respectively.

In the early 20th century, another approach to engineering sciences emerged, namely, systems engineering[2] with roots in the Bell Telephone Laboratories. At

[2] Lightsey (2001), based on (Chestnut, 1967) defines systems engineering as follows: "[…] an interdisciplinary engineering management process that evolves and verifies an integrated, life-cycle balanced set of system solutions that satisfy customer needs. It also provides for simultaneous product and process development, as well as a common basis for communication. Systems engineering ensures that the correct technical tasks get done during development through planning, tracking, and coordinating."

the fundamental level, it is a holistic method to conceive, design and make systems as a whole (Chestnut 1967). As an interdisciplinary field of engineering, it is focused on artefacts and processes over their life cycle (Kossiakoff et al. 2011; Lightsey 2001). Today, this is a widely used approach in many different industries, including but not limited to industrial engineering, computer science, the automotive industry, and the aircraft industry.

These approaches represent different understandings of the engineering sciences, grounded on different philosophical principles. Rankine and the French bridge engineers represent the rational approach to engineering with the focus on applying scientific knowledge to the designing of artefacts, while Thurston and the Americans represent the empirical approach, which begins with observations. Systems engineering represents the movement from rational and empirical views to a holistic philosophy of designing and making systems. Despite the differences, all three approaches of engineering lean toward the technical view of engineering (thing-metaphysics), with an emphasis on the study of objects (entities, properties, and relationships) and methods.

3.2.2 History of Design Sciences

According to different scholars, the modern history of design is rooted in two historical methods of practice (Buchanan 2009): the craft method, based on trial and error; and design focused on drawing and draftsmanship. The former was a trial-and-error method for gradually developing a better understanding of the artefact and its form, which was to be adapted to particular circumstances. The latter is a more analytical way of visualizing and representing a product for various purposes (function) to release the design from the costly activity of prototyping (Jones 1992).

Modern design science emerged in the 20th century (Channell 2009). According to Cross (2001), there were two periods in the history of modern design science that had a significant impact on the view of the relationship between design and science: the 1920s, when the focus was on scientifically designed products (design as applied science), and the 1960s, when the focus was on scientific design activity (design as a scientific activity).

The first period was concerned with rationalizing or making designed objects objectively by pulling knowledge from the sciences to satisfy customer needs and desires with the minimum use of energy and material. Many authors refer to the works of van Doesberg (1923) or Le Corbusier (1929) or to developments at the Bauhaus (Buchanan 2009). Le Corbusier, for example, described the house as an objectively designed "machine for living" (Corbusier 1929):

> The use of the house consists of a regular sequence of definite functions. The regular sequence of these functions is a traffic phenomenon. To render that traffic exact, economical and rapid is the key effort of modern architectural science.

The first methods movement took place during the second period in 1962 at a conference in London (Jones 1963). The focus was on the rationalization of design activity by basing its development on novel problem-solving methods. The methods movement was concerned with sequences, phases of design (analysis, synthesis, and evaluation), principles and design goals (Evbuomwan et al. 1996). Systems theory, operations research, and decision-making techniques were the prime sources of inspiration because of their successful application in World War II and National Aeronautics and Space Administration (NASA) projects (Bayazit 2004; Cross 2001).

J. Christopher Jones, Bruce Archer, Horst W. J. Rittel, and Christopher Alexander have been recognized as key figures in the design methods movement (Bayazit 2004; Buchanan 2009; Cross 2001). According to Buchanan (2009), Jones employed a rhetorical strategy that emphasized memory and invention, including creativity; Archer pursued a productive science strategy that emphasized the act of designing; Rittel pursued a rhetorical strategy that emphasized design as argumentation; and Alexander pursued a strategy based on the dialectical method. The 1960s culminated with the work of Herbert Simon, who defined “the science of artificial” (Simon 1981).

However, in the early 1970s, the first design methods movement was criticized by its early pioneers, including Alexander (1971) and Jones (1977). As active designers, their opposition arose because there was little evidence of success applying scientific methods. When distinguishing the design activity from rational methods, Rittel and Webber (1973) recognized that the design task was subject to ‘wicked problems’; i.e., design problems are subject to the diversity of perspectives, values, and objectives of different stakeholders: they require interpretation. This new perspective was the basis for many new theorizations of design, such as user-centered design, participatory design (co-design) and human-centered design (Giacomin 2014; Norman 2005; Sanders and Stappers 2008; Steen 2012).

According to Cross (1993), Rittel saved the design methods movement by calling for a paradigm shift. Rittel proposed a new argumentative method as the basis for a ‘second-generation design methods movement’ (Bayazit 2004). The second methods movement adopted a constructivist approach, where user involvement in a continuous discussion was considered the key to determining objectives and making decisions. At the same time, methods from different fields, including behavioral sciences, rhetoric, and semiotics were employed (Buchanan 2009).

Like the engineering sciences, design sciences were first concerned with the application of scientific knowledge to the design of new artefacts. In the 1960s, the focus shifted to making design activity more systematic by applying rational and formal methods. In the 1970s, however, there was a shift from a rational and formal conceptualization of design activity to a social one. Thus, by the 1970s, two competing conceptualizations of design activity, namely the technical and social, had emerged.

3.2.3 History of Design Management

As with the engineering and design science, there is no definite beginning of design management as a discipline. Moreover, design management is often not even considered a scientific discipline in its own right, but rather something uniting various disciplines, such as design, engineering, and management. In this section, design management in industrial product development and in the construction industry are juxtaposed.

The first practices of design management were documented in Germany in 1907 (Schwartz 1996): twelve architects and business firms established the Deutscher Werkband (German Work Federation) to compete with the UK and US in the integration of craft and industrial mass-production techniques. Peter Behrens, who demonstrated the practicalities of the Werkband initiative, is regarded as the first industrial designer, and his work can be considered the first contribution to design management (Bürdek 2005).

In the first design methodologies movement in the 1960s and 1970s (Cross 1993; Jones 1963), design evolved from focusing on its aesthetic function into actively cooperating with industry. Methods, tools, and checklists were developed to structure design processes and decisions. Thus, the first design methods movement in the context of design management can be considered a simple tool-making period (Cross 1984; Emmitt 2010; Emmitt and Ruikar 2013).

At the start of the 1990s, notable works in the field by Oakley et al. (1990) and Gorb (1990) and later by De Mozota (2003) were published. Methods for design management were developed, including those for the improvement of team communication, such as the design structure matrix (Steward 1981), quality function deployment (Akao 2004), and concurrent engineering (Eppinger 1991). The main issues covered by design management literature included design leadership, the design process, corporate identity, and the involvement of design management at the operational, tactical, and strategic levels. The primary focus was on the integration of design into organizational infrastructure, and this was the basis for methods such as concurrent engineering (Emmitt 2010).

In parallel with industrial design management, architectural management emerged in the 1960s (Emmitt 2010). The need for architectural management arose because most architects lacked the managerial skills necessary for organizing complex construction projects. "The Architect and His Office" report concluded that architectural practices were too small and lacked management skills. Design business administration and management issues in architecture were left to be learned by osmosis in the work-place (Emmitt 2010). This was partially due to a general lack of interest and a focus on the artistic side of the work rather than on the design process.

Thirty years later, RIBA published a series of new reports under the title 'Strategic Studies', which echoed that little had changed (Emmitt 2010). This was, according to Powell (1997), the reason for the marginalization of the architectural function in building design.

By 2000, two schools of design management were reported in the literature (Emmitt 2010; Gray and Hughes 2001). In addition to traditional project management, design management based on the lean philosophy and principles had emerged. Initially, lean design management focused on the management of design activity, specifically, from the process perspective (Ballard 2002; Ballard and Koskela 1998; El. Reifi and Emmitt 2013; Emmitt 2011; Tzortzopoulos and

Formoso 1999). Over time, there has been a shift in lean design management towards a consideration of social issues. For example, the Last Planner System is now being incorporated in the design process (Hamzeh et al. 2009), and dynamic briefing strategies for capturing customer value have been proposed (Emmitt and Ruikar 2013; Emmitt et al. 2004; Othman et al. 2004).

To summarize, design management seems to have been influenced by the general trends of the particular industry in which it has been practiced. In the early 20th century, in industrial product development, design management was inspired by developments in the domain of scientific management. In the 1960s, design management became management of the design activity. In the early 1990s, design management shifted from managing the design activity to managing the social dimension of the design process.

In the construction industry, up until the 1960s, there was no systematic management of design processes. By 2000, two schools of design management were being developed and implemented in building design management, mainstream project management and lean design management. At first, lean design management was concerned solely with management of the design process (simply producing designs), but later, it began to focus on the management of design as a social process (design projects delivered by designers).

3.2.4 Section Summary

The origins of all three disciplines of productive sciences – engineering, design, and design management – can be either directly or indirectly connected to trends that emerged back in the period of the early industrial revolution, and thus, to the Enlightenment. All three disciplines were influenced by the social, economic and intellectual forces surrounding them. All three disciplines emerged initially based on the attempt to apply scientific knowledge to the issues at hand – to the designing or engineering of artefacts or managing of the design process.

In engineering, two schools emerged in parallel, the rational and the empirical, where the former emphasized theory over practice, while for the latter theory and practice were considered equally important. Systems engineering emerged as a holistic approach to designing and managing systems and processes. However, all engineering disciplines still adhere to the technical/systematic view of engineering, the science of structure, i.e., the study of the properties and relations of the elements within and between different domains or methods of engineering.

In the design discipline, in the beginning, the focus was also on the application of scientific knowledge. In the 1960s, interest shifted from the product to design, but the focus was on the rationalization of design activity. In the 1970s, Rittel proposed a second generation design methods movement, an approach founded on the idea of design as a social process, subject to a designer's intuition, creativity, and social context.

In design management, different schools are not as distinguishable as in the case of engineering and design. In the two different industries considered here, industrial product development and building design management, design management also changed its focus from the product to the process and later to the management of design as a social process.

3.3 Research Paradigms Relevant For Design

In this section, three well-established contemporary research paradigms are studied to understand the philosophical framing of the different kinds of design theory. In the context of design, these are positivism (Hubka and Eder 1996; Simon 1981), constructivism (Buchanan 1992; Buchanan 2009; Cross 2007), and pragmatism (Dalsgaard 2014; March 1984; Rylander 2012).

3.3.1 Positivism

In the positivist paradigm, reality (natural phenomena) is independent of the mind (observer) and knowable and explainable by immutable laws, whatever their complexity (de Figueiredo and da Cunha 2007). The aim is to study or discover truths about the reality (entities, properties, and the relationships of natural phenomena) external to one's consciousness. Thus, the positivist paradigm is based on objectivistic and empirical philosophy (Losee 2001) and sometimes also referred to as the 'scientific method' (Creswell 2013).

Positivist inquiry relies primarily on quantitative and deductive approaches. Reason (concepts and theories) is the source of knowledge, verified in the world; i.e., a provisional idea is proposed and then systematically examined and tested through experiments. In this type of research, quantitative and statistical measures are used to measure the reliability and validity of a theory.

However, often, many assumptions regarding a phenomenon, its elements, and its environment are made, such as where to draw boundaries, the fixation of the qualitative and structural characteristics of a system, with the focus on states instead of change (Allen 2014). The whole process of scientific inquiry is assumed to be objective, unbiased and isolated from human interpretation (McGregor and Murnane 2010).

In the context of design, this can be seen as an attempt to externalize a designer's knowledge (Gregory 1966; Hubka and Eder 1996; Simon 1981) of the product (scientific and technical) or design process. Positivistic design theories are descriptive and focused on verification. However, these descriptive theories often have limited relevance in practice. This was the main criticism levelled against the first design methods movement (Jones 1977), and later also against construction design management (Barrett et al. 1999).

Engineering, in general, has also been considered a mere application of scientific knowledge (de Figueiredo 2018). Thus, its focus has been on abstraction, the use of analytical methods and symbol systems, which, according to Shchedrovitzky (1966), is central to the emergence of specialized disciplines.

A typical example of the application of the positivist approach to engineering is in the design of energy and cost efficient buildings. The modelling and simulation of building energy use are limited to the study of the impact of different combinations of the properties of structures, such as windows, the roof, or walls.

However, the environment within which the building operates is often abstracted away using statistical averages (e.g., average occupancy, lighting, equipment schedules) (Pikas et al. 2017; Pikas et al. 2014). Although some studies have focused on the environmental conditions of a system, they have taken a positivist approach and focused on the fixation of categories, variables, and structures. For example, this was the purpose of an investigation by Ahmed et al. (2016) when determining the hourly consumption profiles of domestic hot water use.

3.3.2 Constructivism

The constructivist approach has its roots in the social sciences. It is based on the phenomenological hypothesis (de Figueiredo and da Cunha 2007): “we gain an understanding of the reality by constructing knowledge through our interactions with the world”. The constructivist paradigm seeks through systematic reflection (interpretation) to determine the essential properties and structures of “the world of human experiences” (Collis et al. 2003; El-Bizri 2006; Louis et al. 1994). For constructivists “reality is socially constructed" (Mertens 1998) and thus, observer-dependent. According to Creswell (2013), constructivists use the grounded theory method to "generate or inductively develop a theory or pattern of meanings". They rely for the most part on qualitative research methods, but quantitative methods are also used.

Another concept central to constructivist research is the idea of the temporal emergence of human experience and behavior, meaning that the perception of reality is a reaction to a changing situation (Johnston 2001). In the constructivist view, material and human agencies are mutually and emergently productive of one another, that is, they are coevolutionary: knowledge changes by interaction with a changing world (including other subjects).

In the context of design, Love (2003) argued that “the concept of design as a social process accords with the constructivist position on knowledge generation, and is widely supported in the design research literature”. According to Buchanan (1992), Rittel and Webber’s proposal for using rhetoric can be considered a constructivist vision, meaning that the designer tends to rely upon the "participants' views of the situation being studied". The constructivist view influenced the formalization of "wicked problems" by Rittel and Webber (1973), and is thus, connected with the essence of the design problem as a problem involving the different perspectives, values, and objectives of different stakeholders.

In design, the constructivist view is especially useful when information is either unstructured or missing, e.g., when designers seek to understand the dynamic and diverse use situations of customers and/or users; i.e., understand the goals, behaviors, and experiences of users and customers in relation to the artefact being designed (Strömberg et al. 2018; van der Bijl-Brouwer and van der Voort 2014; van der Bijl-Brouwer and van der Voort 2014). However, the main limitation of the constructivist view is that it in a sense abstracts away the objects and production of designs. Melles (2008) argued: “Theory fashions in design, such as human-centered, user-centered, collaborative design, interaction design, universalize particular aspects or perspectives on the design process while simultaneously removing designed objects and their production from material and symbolic contexts."

3.3.3 Pragmatism

Pragmatism emerged at the end of the 19th and beginning of the 20th century with Charles Sanders Peirce (1839–1914), William James (1842-1910), Georg Herbert Mead (1863-1931), and John Dewey (1859-1952) (Cherryholmes 1992). Peirce is generally acknowledged as the father of pragmatism (Rylander 2012), which he seminally formulated in his paper 'How to Make our Ideas Clear' (Peirce and Hetzel 1878) as:

> [...] consider what effects, which might conceivably have practical bearings, we conceive the object of our conception to have. Then, our conception of these effects is the whole of our conception of the object.

However, Peirce's ideas remained unnoticed until William James, who made pragmatist ideas more widely known. The third figure to advance "classical pragmatism" was John Dewey, whose work has influenced the design domain (Buchanan 2009). Georg Herbert Mead also made significant contributions to the development of pragmatism (Rorty 1990).

Peirce and James used the term "pragmatism" to designate a method, principle or "maxim" for clarifying concepts and hypotheses and for guiding philosophical disputes that follow from the acceptance of a belief. Philosophical questions with no practical consequences were held to be not of interest (Dalsgaard 2014).

Central to pragmatist thinking is the idea that theories must be linked to experience or practice. Inspired by an evolutionary perspective and rejecting Cartesian radical doubt and dualist worldviews, the dualities of mind-matter, reason-emotion, theory-practice, individual-community and so forth, pragmatism emphasizes interaction and integration (Rylander 2012). Continuity is the guiding principle, resulting in an epistemology that begins with experience and emphasizes processes and experimentation (Rylander 2012). Pragmatism also does not favor any one system of philosophy or reality to another one (Creswell 2013).

However, at the core of Peirce's philosophy was abduction (Peirce and Buchler 1955):

> If you consider carefully the question of pragmatism you will see that it is nothing else than the question of the logic of abduction. That is, pragmatism proposes a certain maxim which, if sound, must render needless any further rule as to the admissibility of hypothesis to rank as hypothesis, that is to say, as explanations of phenomena held as hopeful suggestions.

This passage highlights the importance of abduction, a type of inference for discovering new ideas (explanations), in the pragmatist inquiry. For this reason, design as a creative enterprise is seen to rely on abductive inference (Koskela et al. 2018). Therefore, Melles (2008) argued, pragmatism was based on abductive inference, which in its "[…] both instrumental and critical forms is a robust epistemological and methodological terrain for design research", making a call "[…] to justify its mixed methodology, legitimize its disciplinary status, and move beyond theory fashions". However, Melles continued and argued that the "vulgar discourse of pragmatism", the "[…] straight-line instrumentalist readings of pragmatism misrepresent the Deweyan perspective on the distinctive critical and social value of the Arts and Sciences", extracting "[…] designing from social and ideological context" (Melles 2008).

Drawing on the work of John Dewey, Rylander (2012) and Dalsgaard (2014) summarized the key pragmatist concepts relevant to design conceptualizations: theory and practice (context, situation, and experience) are inseparable; the world (there is an external world, and there is temporal stability) is in constant change and emergent, supporting the experiential view; human activity is situated in context (including thoughts, action, objects, and events), consisting of a subject and the surrounding environment (other people, artefacts, physico-spatial surroundings, and social constructs, including norms and rules); situations are determinate or indeterminate ("its constituents do not hang together" (Dewey 1998)); an indeterminate situation provides the impetus for the subject to initiate an inquiry into the situation to transform it; the initial comprehension of a situation is based on past experiences. The dialogical process of pragmatist inquiry is carried out in several steps (Dalsgaard 2014):

- the subject recognizes the problematic nature of the indeterminate situation;
- the indeterminate situation establishes the motivation to transform it;
- inquiry begins with the identification of elements causing indeterminacy (problem cause) and the framing of the situation (boundaries and properties);
- the subject forms conceptualizations — ideas, theories, and hypotheses — on how to transform the situation; and
- the subject puts conceptualizations in practice to see if they can move the uncertain situation towards resolution.

On the basis of Deweyan pragmatism and the concepts outlined above, Dalsgaard (2014) has developed an argument that also contributes to the efforts to articulate a design inquiry in the pragmatist context (for review, see also Melles (2008)).

3.3.4 Design Paradigms

Taking support from the views of the Russian philosopher G. Shchedrovitsky, Bedny argued that 20th century epistemologies could be divided into two contrasting, non-exclusive, approaches (Bedny and Meister 2014):

- **Naturalistic approach** – individuals are concerned with descriptive studies of transforming unmediated experiences directly into knowledge about the existence of objects and phenomena in nature;
- **Activity approach** – the meaning of human activity (things and events, features and relationships of those things and events) and its

context are only revealed through a process of human inquiry (making it useful for practical interventions).

The design paradigms dichotomizing design as a technical (positivist) or social (constructivist) phenomenon have taken the naturalistic approach, making knowledge claims about things as they are. Fewer paradigms have adopted the activity approach (pragmatism). The essential difference between the naturalistic and activity approaches is that the naturalistic approach considers how something is, studying the design object and activity (positivism) or conscious human experiences (constructivism), while the activity approach also investigates how something ought to be, taking into account agency, the cultural and historical context, and ethical and aesthetic considerations.

In the design domain, four well-known design paradigms have been distinguished. Dorst (1997) differentiated design paradigms based on the three dimensions of design conceptualization: the designer, the design task, and the dynamics of the design process. The first characterizes the designer, what he or she does and how he or she behaves; the second describes the intricacies of how a designer understands the design task; and the third classifies the activities of a designer as macro-, meso-, or micro-level process. Dorst (1997) proposed two paradigms of design, 'rational problem-solving' and 'reflective practice'. Stumpf (2001) added to this list design as a 'social process' and 'hypothesis testing'.

Positivist rational problem-solving, also known as the information-processing view of design conceptualization, was formalized by Simon (1981). A 'second-generation' design paradigm, influenced by the constructivist paradigm, was proposed by Rittel and Webber (1973) and Rittel (1984), who defined design as a social process subject to the problems that are 'wicked' in nature; i.e., require interpretation of different views. In the social process paradigm, the central issue is the communication between different stakeholders when framing and reframing design situations (Bucciarelli 2002). A third design paradigm emerged as a response to the limitations of rational and social design paradigms and is referred to as hypothesis testing (Broadbent 1984; Lawson 2006): designers progress by proposing solution ideas first and testing these against the given situation and problem. The fourth design paradigm is referred to as a reflective design process (Schön 1984), describing the design as the dynamic, continues, cyclic, and unfolding process of learning.

The rational problem-solving and social conceptualizations of design activity lean towards a naturalistic approach to design conceptualization. Hypothesis testing and experiential learning lean towards the activity-based conceptualization of design.

These design paradigms are, however, not necessarily mutually exclusive, but may even be considered complementary (Bedny and Meister 2014). For example, activity theory, adopting the ontology and epistemology of activity approach, can facilitate the development of holistic design theory, incorporating descriptive and prescriptive dimensions of designing (Bedny and Meister 2014). A few examples based on the activity theory to conceptualize design have been proposed (Cash et al. 2015; Von Saucken et al. 2012).

3.3.5 Section Summary and Discussion

All three research paradigms, the positivist, constructivist and pragmatist, have been used to frame design, supporting specific underlying assumptions regarding metaphysics, ontology, epistemology, and methodology. These assumptions have had a profound impact on inquiry in related subject areas, methods of thought and action, and the guiding principles of design, engineering, and management.

The positivist paradigm leans towards thing metaphysics, while the constructivist and pragmatist paradigms lean towards process-based metaphysics. Ontologically, the positivist paradigm assumes that reality is observer-independent and knowable and explainable by immutable laws (single reality). According to the constructivist paradigm, reality is considered observer-dependent, and as reality is socially constructed, there are multiple perspectives. The pragmatist paradigm assumes that reality can be conceptualized in multiple ways (pluralism), not just from multiple perspectives, as in constructivism. Reality is emergent, and a person and situation are inseparable.

Epistemologically, the difference between the various philosophical positions lies in how theory and observation/practice are related. According to the positivist view, although empirical sensory experiences are the starting point, true knowledge arises from reason and the development of conceptual models verified in the world. The positivist research paradigm focuses on the study or discovering of the truths of reality (properties and relationships of natural phenomena) using the deductive method. Positivists are keen to use analytical methods and symbol systems to study phenomena. Problems emerge, however, when scholars do not differentiate between the abstract and the real. According to Newberry, this was argued by Levins and Lewontin (Newberry 2015):

> [...] abstraction becomes destructive when the abstract is reified and when the historical process of abstraction is forgotten, so that the abstract descriptions are taken for descriptions of the actual.

According to the constructivist research paradigm, knowledge of reality arises from systematic reflection, which leads to an understanding of the essential properties and structures of (different) subjective experiences, i.e., an understanding and interpretation of conscious human experiences. Thus, constructivism hinges on humans as the prime source of knowledge; i.e., it is a paradigm of otherness, humans studying humans. The constructivist research paradigm generally adheres to qualitative strategies (the grounded theory approach; the inductive development of a theory or pattern of meanings), although quantitative strategies may also be followed.

Pragmatist research philosophy is concerned with the study of practical consequences (effects and qualities), which are knowable through action and interaction with a problematic situation (context, situation, and experience). The pragmatist paradigm has no set predispositions, focusing on what is productive in the transformation of the given problematic situation into a more desirable one. It is proposed here, that pragmatism is concerned with the situated object and subject-oriented activities, the dynamic and changing elements of human action, and practical consequences. Reality and knowledge of reality emerge from a continuous process of experimentation directed at changing a situation.

The design conceptualizations of Simon (1981) and the first design methods movement were primarily guided by the positivist research paradigm. The constructivist approach emerged when Rittel and Webber (1973) proposed a shift to the social process view of design conceptualizations. This is about ten years after Kuhn (1962) published 'The Structure of Scientific Revolutions'. However, the positivist and constructivist approaches, i.e., the rational problem-solving and social conceptualizations of design activity, are both essentially naturalistic approaches to conceptualizing design. Hypothesis testing and experiential learning were leaning towards the activity-based approach to design. Descriptive and prescriptive conceptualizations of design activity focused on describing the as-is and to-be, respectively. Although constructivism and pragmatism are not necessarily conflicting views, they have a different function; constructivism aims to understand presence and innate human experiences, while pragmatism is concerned with the future and how things are and should be.

It is, therefore, proposed that pragmatism is the proper philosophical view of design theory. If design should lead to how things ought to be, then pragmatism is the philosophy of these consequences, or more precisely, it is the philosophy of the production of those consequences. **Table 5** summarizes the different research views and provides representative examples of design.

Table 5. Summary of research paradigms relevant to the framing of design conceptualizations.

Characteristics	Positivism	Constructivism	Pragmatism
Metaphysics	Thing (universals)	Process (changing views)	Process (changing situations)
Ontology	Observer-independent and single reality (knowable and explainable by immutable laws)	Observer-dependent and multiple perspectives (socially constructed)	Pluralism of realities (emergent and inseparable from a person and a situation)
Epistemology	Study or discover truths about reality (objective claims)	Study and systematic reflection leading to an understanding and interpretation of essential properties and structures of human experiences (subjective claims)	Study of practical consequences (effects and qualities) (subjective and objective claims)
Methodology	Quantitative approach (statistical and experimental)	Mostly qualitative (grounded theory approach; inductively develop a theory or pattern of meanings)	Quantitative and qualitative (continuous process and experimentation directed at changing a situation)
Approach	Naturalistic (as-is)	Naturalistic (as-is)	Activity approach (as-is and to-be)
Representative Design Examples	Focus on externalization, description, and verification of a designer's knowledge of the product and process, emphasizing abstraction, using analytical methods and symbol systems (e.g., Hubka and Eder, 1996, Simon, 1981).	Design problems are "wicked" due to the different perspectives, values, and objectives of different stakeholders; designers rely on the views of participants of the situation under study. (Rittel and Webber, 1973)	An indeterminate situation provides the impetus for the subject (designer) to initiate inquiry into a situation with the aim of transforming it. Human activity is situated in a context. (Rylander, 2012; Dalsgaard, 2014)
Design Paradigms	Design as rational problem-solving or information processing (Simon, 1981)	Design as a social process (Rittel and Webber, 1973, Bucciarelli, 1994)	Reflective practice (Schön, 1984) and hypothesis testing (Broadbent, 1984, Lawson, 2006)

3.4 Chapter Summary

In this chapter, an overview of the philosophical concepts relevant to the framing of design conceptualizations was developed. The following questions were investigated: What ideas of philosophy are relevant to design conceptualizations? How were the different disciplines of design philosophically grounded when they emerged? How are contemporary productive sciences philosophically grounded? The following areas were addressed: metaphysics, ontology, epistemology, the primary types of reasoning, inquiry, and methods.

Metaphysics is the underlying meta-view of the world. It describes the focus of the productive sciences, and the focus is on either the static or dynamic aspects of the artefact or process. In both cases, the focus can in turn be on either the descriptive or prescriptive dimensions of the design object or activity. For example, although design activity is processual, design activity conceptualization can focus on a description of the design process structure (phases, inputs, outputs). In the present research, design is conceptualized as a human activity consisting of mental and external actions and operations from which things emerge, including the product as an output of the design process. Thus, design is conceptualized on the basis of process metaphysics.

Ontology is the field of study concerned with the categorization of things (observer-independent or observer-dependent), and epistemology is concerned with knowledge, the relationship between theory and observation/practice and between subjective and objectives claims. Pluralist ontology can explain the complex relations between designers, models, and the design objects, which often do not exist at the beginning of a design inquiry. Epistemology establishes the relationship between these different domains, guided by methodological questions. Methods of inquiry (establishing design activities) and the processes of things (what happens to design information) are either analytic or synthetic.

Modern productive sciences emerged during the early industrial revolution. All three, which are considered here, the engineering design, design science and design management disciplines were influenced by social, economic and intellectual forces, and all applied reason, reductionism, and the scientific method to the designing or engineering of artefacts or the management of productive processes. Over time, alternative approaches to the description and development of new practices emerged on the basis of new philosophical paradigms.

The principal paradigms of the 20th century for conceptualizing design were positivism, constructivism, and pragmatism. The majority of design conceptualizations approached design from either the positivist or constructivist perspective and were naturalistic, descriptive conceptualizations of design. Pragmatism is based on the activity approach. The pragmatist paradigm of transforming a given conflicting situation into a desired one is proposed here as the proper philosophical basis for productive sciences, as it is a philosophy oriented to the production of expected outcomes.

Put a point in motion, and you will create a line,
put the line in motion, and a surface will arise,
put the surface in motion, and you will create space,
put space in motion, and time will emerge,
put time in motion, and you will set matter in motion,
give a push to life, a shove to death, a push to spirit,
the spirit is stirring, causing a rebellion,
why at its foundation just a point, at the root of all just a line.

H.Runnel, "*Creation*"

4. Two Ancient Strategies of Inquiry

Contemporary design conceptualizations are eclectic with many different sources of inspiration. The fragmentation of design theories suggests that there is a lack of consensus among design scholars (Buchanan 2009; Love 2000). A way to address this issue is to go back to first principles. Aristotle provided the first account of the productive sciences applying the method of analysis and rhetoric, which most contemporary design scholars have neglected. In this chapter, the intent is to determine the requirements for a theory of design. Why is it justified to recognize the method of analysis and rhetoric as models or theories of design? What are the key concepts and principles of the method of analysis and rhetoric? Do the two strategies of inquiry have contemporary analogues or share features with contemporary conceptualizations? The expected output of this chapter is the development of a conceptual framework for the construction of a new design model and justification for the application of the two ancient strategies of inquiry.

This chapter is divided into five sections. In section 4.1, the elements and concepts of theory and design theory are studied. In section 4.2, the Aristotelian productive sciences are reviewed and compared to two authoritative contemporary conceptualizations of design. In section 4.3, the key concepts and principles of the method of analysis and rhetoric are studied and then compared to the current methodical and theoretical landscape of design. In section, 4.4, the method of analysis and rhetoric are mapped to the six design theory elements proposed by Gregor and Jones (2007). Section 4.5 summarizes the ideas presented in this chapter.

4.1 Theoretical Framework for Design Theory

To assess whether the method of analysis and rhetoric are suitable candidates for design theorization, the question of what constitutes a design theory is addressed. More specifically, what are the key characteristics and elements of a unified theory of design? The treatment below extends the discussion in subsection 1.1.2.

4.1.1 Evolution and Challenges of Design Theorization

Theories are subject to evolution. Kuhn (1962) proposed that the progress of scientific disciplines is characterized by two modes of inquiry: the normal science and paradigm change. Normal science occurs when the scientific community operates according to the well-established research paradigm. However, occasionally, the identification of anomalies, in theory, leads to the introduction of new research paradigms. For example, in the 1970s, on the basis of the constructivist research paradigm, the second design methods movement was introduced to address the lack of success applying formal methods to design and design activity (Buchanan 2009).

Taking another approach, Deutsch (2011) argued that sciences are advanced through specialization and unification. In the design domain, the increasing specialization of design theories has been notable over the last several decades, resulting in "theory fashions" (Melles 2008) and "disintegrated mutually inconsistent design theories" (Galle 2008). However, in recent decades, there has been a general interest in the development of a unified theory of design and designing (Gero and Kannengiesser 2014; Le Masson et al. 2017; Love 2002; Suh 2001). Despite extensive research across many different domains from a variety of perspectives, no unified theory of design has yet emerged (Galle 2008; Love 2000). For example, Dilnot (2018) argued that "[...] we still do not have an adequate intellectual comprehension of design in the fullest sense of the term. We do not, in many ways, yet have design knowledge".

According to Love (2002), the failure to develop a unified theory of design can be attributed to the following: neglect of philosophical issues (ontology and epistemology) in theory-making; domain-specific approaches to design theorization; lack of agreed definitions and terminology for core concepts; and poor integration of theories across disciplines. Love (2002) argued that the consequences of the failure to develop a unified theory of design have included the following: oppositions between design researchers, especially across domains; the challenging task of validating the theories; a lack of clarity regarding boundaries and scope; and the challenging task of communicating and teaching design knowledge. This thesis will address the reasons for the lack of a unified theory of design, as outlined by Love.

4.1.2 Characteristics of Design Theory

The term theory has an ambiguous meaning, often used interchangeably with terms such as philosophy, concept, model, system, etc. Four different meanings can be distinguished (Gregor and Jones 2007; Koskela 2000; Love 2002): opposition to practice, hypothetical speculation, general principles of any science or field, and an individual discrete theory. Badke-Schaub and Eris (2013) argued that a proper design theory is "[...] a body of knowledge which provides an understanding of the principles, practices, and procedures of design". In the present research, the term design theory refers to the description of the general principles of a situated design activity.

Design activity is part of the universal phenomenon of production. Koskela (2000) argued that "in modern operations management, it is often thought that production consists of three core phenomena: product development, order delivery and production proper, which all face the customer". These three phenomena are, moreover, interrelated, and different types of production can be distinguished based on the configurations of these interrelationships. Production theories define common goals (delivery of the product, expected characteristics of production, and customer goals), the causal structure between the goal and individual actions, and guidelines for managerial actions, which, on the most abstract level, consist of the design, execution, and improvement of the production system. The functions of production theory include the following (Koskela 2000): an explanation of observed behavior, the prediction of behavior connected with goals, directions for progress, and a means to test validity. Production theories also direct and facilitate the development of methods and tools for practice, a common language for communication, the training of novices, and the transfer of practices. Production theories have elements that are both independent of and dependent on the situation. The validity of production theories is measured in relative terms (Koskela 2000).

As in the case of production theories in general, in addition to explanation and prediction, the function of design theories ought to include prescriptions for design actions. This means that design theories should provide guidance (directions and methods for testing) for the "development of design practices; understanding of different methods; different perspectives on problems that were previously unclear; and change practices" (Weisbrod and Kroll 2017). Thus, design theories should contain both descriptive and prescriptive elements (Stumpf and McDonnell 2002): principles of design and designing, leading to a testable hypothesis on how designers should work.

4.1.3 Elements of Design Theory

In the general scientific literature and in the design domain, different schemes for the concept of theory have been proposed. Relying on the work of Robert Dubin, who studied natural and social sciences, Whetten (1989), for example, argued that (social) theories should contain four elements:

- **What.** What factors (variables, constructs, and concepts) should be considered part of the explanation of the phenomena of interest.
- **How.** How are the factors related (causality)?
- **Why.** Why choose these factors? What explains the causal relationships?
- **Who, where, when.** What are the scope and boundaries of the theory?

Love (2000) proposed a philosophical meta-theoretical method of design research. For Love, as in the present study (see chapter 3), the underlying phenomenon of design is the situated design activity of a human agent. Proceeding from this premise, Love argued that design theories should address ontological (assumptions about reality) and epistemological questions, general theories explaining human activities and their relationships, internal and collaborative processes, process structures, methods, decision-making mechanisms, the behavior of designed objects, and the conception and labeling of reality. As Simon (1981) had earlier argued, according to Love (2002), design theories need to address design processes, as designed objects are inextricably linked with these. However, as Love (2002) stated himself, "the meta-theoretical hierarchy [framework] is not well suited to developing theories".

Building on Dubin, Simon, and design science research, Gregor and Jones (2007) argued that any design theory should contain a minimum of six elements, four of which correspond to the four elements proposed by Whetten (1989): (1) purpose and scope (boundaries), (2) constructs (factors, units of interest), (3) principles of form and function (relationships between factors), (4) artefact mutability (product or process system states), (5) testable propositions (predictions), and (6) justificatory knowledge (product or process kernel[3] theories). Quality criteria for the development of the design theory also needs to be defined. Galle (2008) proposed 'consistency', 'viability', 'elegance', 'philosophical relevance for design', and 'theoretical relevance to design' as the most germane.

4.1.4 Core Design Concepts and Definitions

Love (2002) proposed a set of design theory components that describe the factors of interest and the relationships between them, i.e., what and how according to Whetten (1989), or the constructs and principles of form and function according to Gregor and Jones (2007). Proceeding from three essential elements, 'humans', 'objects', and 'contexts', and their interdependencies, Love defined nine areas of research and theory making (2002): humans, objects, contexts, human-to-human interactions, object-to-object interactions, human and object interactions, human and context interactions, object and context interactions, and interactions involving human(s), object(s), and contexts together. Different scientific disciplines have been dedicated to each of these nine areas. For example, engineering addresses the behavior of objects, object-to-object interactions, and interactions involving human(s), object(s), and contexts together. Research on designs and designing is primarily concerned with interactions involving human(s), object(s) and contexts together, while pulling knowledge from other research areas, with the general aim of bringing about changes in humans, objects and contexts that are enabled and mediated by the situated subject and object-oriented activities. And to bring about change, a designer is making predictions (Galle 2008).

[3] Gregor and Jones (2007) defined kernel theories as "the underlying knowledge or theory from the natural or social or design sciences that gives a basis and explanation for the design".

Furthermore, Love (2002) argued that this could be distilled further by distinguishing between "'internal human processes' and the 'external aspects of the behavior of individuals and groups'". The internal processes of designing individuals include the following (Love 2002): the conscious and unconscious representation of things, the exercise of various cognitive abilities, the formation of values and beliefs, the inflow and outflow of information (communication), and creative acts, both their own and that of others. External processes include the following (Love 2002): how humans collect, compose, classify, and manage data and how they identify, bring together, and manage human expertise. Design activities should also be distinguished from associated activities (e.g., drawing, information search). The internal human processes connected with design are subjective analytical and synthetic methods of inquiry, while external processes are the objective synthetic processes of things.

Identification of the critical factors of design theory (humans, objects, and contexts) and the types of interrelationships between them together with the distinguishing the internal activities of individuals from external ones offers the opportunity to develop clear definitions of core concepts and terms. However, here it is important to note that there are no commonly accepted definitions of design and designing. Love (2000) argued that there is hardly any consensus at all on what design is, that design is a complex phenomenon defined from many different perspectives (design paradigms) and at many different levels of detail.

As a result of the pluralism of approaches and theories, in the design literature, many different definitions for design and designing have been proposed. The following are some examples:

> Engineering design is the systematic, intelligent generation and evaluation of specifications for artefacts whose form and function achieve stated objectives and satisfy specified constraints (Dym 1994).

> [...] 'design' as to conceive the idea for some artefact or system and/or to express the idea in an embodiable form [...] 'Designing' is a process in which all sorts of things are done (drawing, building models, experimenting, etc.), but above all, it is a process of goal-directed reasoning. The reasoning from function to form is [...] a form of reductive reasoning. This means that the conclusions (the design) does not indisputably follow form the premises [...] there are always many good solutions (Roozenburg and Eekels 1995).

> Engineering Design is the use of scientific principles, technical information and imagination in the definition of a mechanical structure, machine or system to perform pre-specified functions with the maximum economy and efficiency (Feilden 1963).

> Design involves a prescription or model, the intention of embodiment as hardware, and the presence of a creative step (Archer 1984).

> Relating product with situation to give satisfaction (Gregory 1966).

> The conditioning factor for those parts of the product which come into contact with people (Farr 1966).

These definitions call attention to particular aspects of design, i.e., designers are concerned with the following (Andreasen 2011; Andreasen et al. 2015): situation (context), needs (voice of the customer), requirements, creativity, functional specifications, structural descriptions, and production/manufacturing processes. Moreover, designers use models to facilitate forethought, capture the unknown, and develop ideas about the artefact under investigation (Maier et al. 2014). It appears that definitions of design and designing have conflated the diversity of ideas, resulting in definitions of designing that are of little use.

According to Love (2002), a consistent and unified theory of design can only be developed when design and designing are defined in a meaningful way. Defining designing also requires distinguishing the different types of human activities (internal and external). Love proposed the following definitions for design, designing, designer, and the social (design) process (2003):

- **'Design'** – (noun) specification for a particular artefact or the undertaking of a particular activity (a design is the basis for production of an artefact – thus, a distinction between the outcomes of designing and the outputs of craft is made). Gero (1990) divided design projects into a routine (no new variables or ranges in values), innovative (variable value ranges are outside the standard space) and creative designs (new variables are introduced).
- **'Designing'** – (verb) non-routine internal human activity leading to the production of a design. In (2002), Love argued that the spectrum of novel and routine designs is a criterion for distinguishing between more and less creative design activities. "In other words, the essential aspect of the human activity of 'designing' relates to those elements of creating a design that is non-routine"[4].
- **'Designer'** – someone who is, has been, or will be designing, i.e., "someone who is skilled at addressing non-routine issues" (Love 2002).
- **'Design process'** – any process or activity that includes at least one act of 'designing' alongside other activities such as, calculating, drawing, information collection, many of which are, or can be, routine or automated.
- **'Social process'** – any process or activity that includes at least one act of social interaction between people alongside other activities (the external aspects of interactions between people).

From these definitions, it follows that designing is a non-routine internal human activity resulting in a specification for a particular artefact or the undertaking of a particular activity. The design process includes at least one non-routine internal activity and associated external activities, often undertaken in social contexts. Furthermore, based on these definitions, Love (2003) proposed relationships between the concepts, stating that the (internal) design activity and design process may be embedded in the social process and vice versa. The (internal) design activity may influence social processes, and already developed designs may influence the design and social processes. This is aligned with the

[4] In terms of the design activity, novelty is a relative, not absolute, concept: an activity may be novel for a novice while routine for an expert designer (Kroll and Koskela, 2017).

three dimensions of design conceptualizations proposed by Dorst (2007): the designer, the design task (problems and solutions), and the dynamics of the design process (the subject and object-oriented activities embedded in the social and design processes). In **Figure 9**, the basic concepts and the relationships between them are depicted.

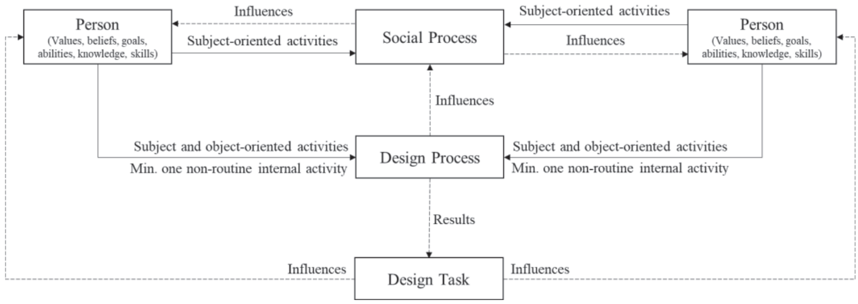


Figure 9. The depiction of core concepts and relationships of design (inspired by Love (2003)).

4.1.5 Section Summary and Discussion

In this section, the evolution, challenges, characteristics, elements, and core concepts of design theory-making were addressed. Scientific disciplines operate in the context of normal science or paradigm change. Theories evolve through specialization and unification. Specialization in the design domain has led to the pluralism of approaches and theories (“theory fashions”). Although many efforts have been made, no unified theory of design has emerged.

In spite of the many interpretations of the term theory, it was argued the general principles of situated human activity apply to design theory because design is a type of situated human activity. Design is part of a more general phenomenon, namely, the production phenomenon. Thus, the same characteristics regarding goals, functions (both descriptive and prescriptive), guidance for practice, and testing of validity in relative terms are also relevant to design theorization.

Different schemas for theory-making in the general scientific literature and specifically, in the design domain have been proposed. For example, Whetten argued in the context of the social sciences that theories should contain at least four elements: what, how, why, and who, where and when. Love, on the other hand, proposed a philosophical meta-theoretical method for design research consisting of ten hierarchically organized and relatively positioned aspects of design theory. However, Love’s method is more suitable to the philosophical investigation of design-related concepts but less appropriate for design theory-building. Gregor and Jones argued that design theories must contain at least six elements: (1) purpose and scope, (2) constructs, (3) principles of form and function, (4) artifact mutability, (5) testable propositions, and (6) justificatory knowledge. These elements together with the criteria (‘consistency’, ‘viability’, ‘elegance’, ‘philosophical relevance for design’, and ‘theoretical relevance to design’) form the requirements for a theory of design and its development.

The three key factors of design theory, humans, objects and contexts, and their states and changes in state are caused by situated human activity and the relationships between these activities. Thus, design is about change (and therefore, also prediction), and this change is possible through human agency (of applied effort). Design activities are internal or external (associated activities): the application of subjective analytical and synthetic methods or the objective synthetic processes of things, respectively. The development of a unified theory of design requires consistent and clear definitions for the key concepts of design and designing. Operational definitions for design, designing, designer, design process, and social process were established on the basis of the work of Love. Most importantly, as part of the design process, designing was defined as an internal non-routine human activity for developing a specification, often embedded in or influenced by social processes.

4.2 Aristotelian Production Sciences and Contemporary Design Conceptualizations

In the following, a brief overview of the Aristotelian concept of productive sciences is provided. Aristotle based his development of the theory of production on the method of analysis and rhetoric. The objective here is to show how the two strategies of inquiry are related to the productive sciences in general and why it is justified to recognize them as models or theories of design. The Aristotelian productive sciences are then compared to two authoritative contemporary works, the work of Simon (1981), who formalized the science of the artificial, and Buchanan (2009), who analyzed the different strategies of inquiry in contemporary design conceptualizations. The comparison is instrumental in justifying (with an appeal to *ethos*) the relevance of the two ancient strategies of inquiry in general and specifically, to the purposes of this research.

4.2.1 Aristotelian Productive Science

Aristotle distinguished five virtues of thought (i.e., character traits), of which the *episteme* (theoretical) and *techne* (productive) are the most relevant in the context of this study (Aristotle 2001; Richard 2008). However, it is important to note here that as argued by Parry (2014), the distinction is not so clear-cut; even Aristotle did not consistently distinguish between the two.

In Book VI of the Nicomachean Ethics, Aristotle distinguished two parts of the rational soul, the calculating part (*logistikon*) and the scientific part (*epistêmonikon*). The calculating part considered things which admit of change, whereas the scientific part considered things which do not admit of change (Parry 2014). Hence, the former focuses on the particular and variable things, the latter on the universal and invariable things.

Theoretical thinking or *episteme* in Greek means “to know”, and it is a type of knowledge that explains questions of “what” and “how” about the world. Sometimes it is also translated as scientific knowledge, though not to be confused with the contemporary understanding of the term ‘scientific’. For Aristotle, the object of knowledge was what was universal and necessary, as opposed to the particular and probable (Aristotle 2001; Bolton 2012).

Practical thinking (as distinct from theoretical) was divided into two types, *phronesis* and *techne*, practical sciences and productive sciences, respectively; i.e., Aristotle distinguished between acting and making something. Both are concerned with intelligent human action but differ in their intentions and goals. Practical sciences are concerned with how one should act in various situations, and its goals and intentions are in the act itself (e.g., playing piano); while in the productive sciences the goal and intention are in the object being produced (Richard 2008). In the practical sciences, an agent deliberately chooses the act for its own sake; while in the productive sciences, an agent chooses his actions for the sake of the end result, an object being produced (Parry 2014). The art of making involves intentional agency; i.e., an artefact must have a maker (Hilpinen 2011).

For Aristotle, rhetoric and the arts, in general, belonged to the productive sciences. Shields (2016) argued that "another form of productive science is rhetoric, which treats the principles of speech-making appropriate to various forensic and persuasive settings, including centrally political assemblies". The process of deliberation and consequential making, as treated by the productive sciences, is subject to everyday contingencies; i.e., production is subject to changing conditions of and in the environment. The productive sciences have little to do with 'law-like' rules (Parry 2014).

In Metaphysics (Book VII), Aristotle described the nature of productive reasoning (as quoted by Koskela (2008)):

> What is healthy comes into being when the producer has had the following sort of thought: since health is this, then if something is to be healthy, it must have this (for instance, a uniform condition of the body), and if it is to have this, it must have heat. This is how he thinks at each stage, until he leads the process back to the last thing, which is what he can produce himself; and then the motion from here on toward health is called a production [....] Production is the motion that proceeds from the last stage in thinking. Each of the other things—those in between—comes to be in the same way. I mean, for instance, that if this [body] is to be healthy, its bodily condition must be made uniform. What then, is it to be made uniform? This. [The body] will have this if it is warmed. What is it to be warmed? This. But this is potentially present. And now he has reached what is up to himself.

The agent begins with the end in mind, such as health, and productive reasoning continues backward from it and concludes in action (Parry 2014). Arguably, Aristotle is thus the first scholar to provide a proper account of the productive sciences, which cover both thinking (deliberation) and production. Furthermore, Aristotle's comment in the Nicomachean Ethics on the theory of production is instructive and points the way to an understanding of design (Aristotle 2001):

> We deliberate not about ends but about means. For a doctor does not deliberate whether he shall heal, nor an orator whether he shall convince, nor a statesman whether he shall produce law and order, nor does anyone else deliberate about

> his end. Having set the end, they consider how and by what means it is to be attained; and if it seems to be produced by several means they consider by which it is most easily and best produced, while if it is achieved by one only they consider how it will be achieved by this and by what means this will be achieved, till they come to the first cause, which in the order of discovery is last. For the person who deliberates seems to inquire and analyze in the way described as though he was analyzing a geometrical construction (not all inquiry appears to be deliberation—for instance, mathematical inquiries—but all deliberation is inquiry), and what is last in the order of analysis seems to be first in the order of becoming. And if we come on an impossibility, we give up the search, e.g., if we need money and this cannot be got; but if a thing appears possible, we try to do it. (Nicomachean Ethics, III, 3, 1112b8-27).

According to Aristotle, there is an affinity between design and the method of analysis. On the basis of this connection to the method of analysis, Koskela (2008) argued that the Aristotelian theory of design (and making) was both deeper and broader than present candidates for a theory of design. Furthermore, Koskela argued that the puzzles and anomalies in the current theorization of design are symptoms of a failure to build on the scientific legacy of Antiquity.

4.2.2 The Science of the Artificial by Herbert Simon

Herbert Simon formalized the "Science of the Artificial" and posed the following question (Simon 1981):

> Natural science is knowledge about natural objects and phenomena. We ask whether there cannot also be "artificial science" - knowledge about artificial objects and phenomena.

Just as Buchanan later argued (2009), Simon (1981) proposed the 'science of the artificial' by re-purposing Aristotle's four causes: matter, form, agent, and end (or purpose). According to Aristotle, to describe the cause of a change or movement, or a need for a change or movement, several answers to the question 'why' need to be given across different combinations of the four domains (Falcon 2015). On this basis, Simon offered his own interpretation of the domain of the artificial (Simon 1981):

- Artificial things are synthesized (though not always or usually with full forethought) by human beings (agent).
- Artificial things may imitate the appearance of natural things without possessing, in one or many respects, the reality of them (matter).
- Artificial things are often discussed, mainly when they are being designed, in terms of both imperatives and descriptives (form).
- Artificial things can be characterized by functions, goals, adaptation (end).

Simon placed design problems in a hierarchy, with the most complex problems at the top to problems of formal scientific inquiry at the bottom, to distinguish design from other disciplines (Simon 1981). At the highest level are practices of daily life, shaped around desires, values, preferences, and intentions, and thus related to complex human behaviors and intelligence. These are often guided by 'rules-of-thumb' or 'cookbook methods' rather than logical and proven methods of reasoning (Pitt 2001). At the lowest level are the natural sciences, which are guided by logical and mathematical strategies of inquiry. Simon called the middle-level methods the 'science of the artificial'. According to Simon (1981), the difference between science and design is in the logic of their reasoning, as the domain of the artificial is a combination of natural laws and human preferences and motivations. Proceeding from this view, Simon encouraged the scientific community to transform design from an art into a science (Simon 1981):

> [...] an explicit, abstract, intellectual theory of the processes of synthesis and design, a theory that can be analyzed and taught in the same way that the laws of chemistry, physiology, and economics can be analyzed and taught.

Therefore, the 'science of the artificial' should explain the complex mental and practical activities of designers. According to Simon (1981), the mental and practical efforts of a designer are "concerned with attaining goals by adapting the former [the mental and practical efforts] to the latter [goals]". Simon proposed that designers use symbolic representations, such as simulations, as a methodical scientific inquiry into the nature of made-things, to understand the interfaces between the inner and outer environment (Simon 1981). This means that designers use conceptual models encoded in symbolic forms, and cognition consists, in part, of symbol processing. This conceptualization of design has come to be known as the information processing view of design (Clancey 1993).

Inspired by the reductionist approach, Simon proposed dividing the design problem into simpler components and mechanisms for computer modelling and then merging these components into wholes to understand the creative act of design and its processes (Clancey 1993). According to Simon, it is this second step, the combining of parts and principles into a whole, which constitutes the creative design task. In this respect, the designer's fashioning of prototypes and efforts at visualization are all simulations that test the designer's understanding of an artefact and the artefact's interfaces, as the inner environment is adapted to the outer environment (Buchanan 2009). On the basis of this idea, Gero (1990) developed his conceptualization of design prototypes as an epistemic means. Thus, computers could be used to simulate artificial systems and aid in their design. This is the connection between the design method and a designer's cognitive processes (the manipulation of symbols and symbol systems in information processing).

The science of the artificial is concerned with purposeful objects, as defined by their structure in a particular environment[5]. Simon (1981) described the artefact as follows:

> Fulfillment of purpose or adaptation to a goal involves a relation among three terms: the purpose or goal, the character of the artifact, and the environment in which the artifact performs.

[5] This contradicts the approach of classical social sciences, where the central subject of study are individuals, and substance or material reality is considered incidental to what individuals or groups of individuals do (Pickering, 1993).

According to Simon, the design environment consists of the artefact's 'inner' environment (substance and configuration of structure) and 'outer' environment (what molds the artefact) (Kroes 2002). Essentially, the question is about the system versus environment split (Von Bertalanffy 1950). The boundary, however, is not arbitrary, but intrinsic, depending on the designer's experience and knowledge, the given situation, and the customer and his or her purposes.

4.2.3 Buchanan's Analysis of Design Strategies

According to Buchanan (2009), the end of the 19th century and the beginning of the 20th mark the start of coherent design inquiry into artefacts (Buchanan 2009). He argued that philosophical pluralism guided 20th century inquiry into design and that three essential strategies of inquiry informed conceptions of the design activity: dialectic, design inquiry (rhetoric and productive science), and design science. Design dialectic and design inquiry are addressed below. Design science was covered in part by Simon's conceptualization of the science of the artificial.

Dialectic has many interpretations, including idealist, materialist, and skeptical variations, but common to all of these is the process of finding a unified idea to resolve a contradiction (Buchanan 2009). Buchanan (2009) described Alexander's dialectical design method (Alexander, 1971) as a process divided into three stages: problem clarification, the finding of the proper geometrical relations or patterns for resolving conflicts, and the combining of these into wholes. Inspired by logic and mathematics, Alexander proposed the use of hierarchical structures, known as pattern language, to represent design problems and solutions.

The kernel of Alexander's design theory lies in the determination of underlying elements in specific domains (the environment and the artefact) and their relations and causality in a network of patterns (problems and solutions), all ultimately leading to the conception of dynamic whole that is rational, constructive, and evolutionary (Buchanan 2009). Thus, Alexander applied dialectical reasoning to the discovery and invention of design practices. Alexander was not explicit regarding the inspiration for the development of his design method, but a clue can be found in a 1971 article, where he was asked about the origins of his method (Alexander 1971):

> As you know, I studied mathematics for a long time. What I learned, among other things, was that if you want to specify something precisely, the only way to specify it and be sure that you aren't kidding yourself is to specify a clearly defined step-by-step process which anyone can carry out, for constructing the thing you are trying to specify. In short, if you really understand what a fine piece of architecture is - really, thoroughly understand it - you will be able to specify a step-by-step process which will always lead to the creation of such a thing. So for me, the definition of a process, or a method, was just a way of being precise [...].

It appears that mathematics inspired the development of Alexander's method. This is an essential insight. As we shall see, mathematics, in particular, the method of analysis, has been the chief source of inspiration for the development of a basic understanding of analytic and synthetic inquiries and the processes of things.

According to Buchanan (2009), another type of inquiry that has influenced design research is design inquiry, a combined conceptualization of both rhetoric and productive acts. In design dialectic and design science, design is focused on what is necessary, but design inquiry seeks to bridge the gap between theory and practice. Designing and making are not separate but are firmly connected views on conceiving and delivering an artefact (Buchanan 2013; Buchanan 1992; Buchanan 2007).

Productive inquiry focuses on an analysis of the primary elements of products (form, function, materials and the manner of production) and a creative synthesis of these elements throughout the product's entire life-cycle (Buchanan 2009). The process of concern is the movement from the identification of functional elements (an artefact's purposes) to an embodiment of the artefact, from parts to whole, with a unifying idea (a vision of the whole solution) in mind. Archer (1968) was representative of this school of thought.

Design rhetoric is an art of discovery involving the imagination and inventiveness of a designer instigating (social) change through argument, communication, and action (Halstrøm 2017). Design rhetoric is focused on the relationship between the expectations of the client/user and the intentions of the designer, as manifested in the product and its refinement in time through continuous negotiations (Stumpf 2001).

However, in his analysis, Buchanan fell short of connecting these strategies of inquiry to the method of analysis. Since its formalization by Euclid (Beaney 2016), the geometrical method has had a great influence on the development of Western thought, rationalism, and empiricism (Asano 1998; Cellucci 2013; Cornford 1932; Losee 2001; Netz 2003). It had already been incorporated in Plato's and Aristotle's view on theoretical and practical reasoning (McKeon 1966; Menn 2002), and it has played a significant role in the evolution of the philosophy of science ever since (Goldenbaum 2015), including the development of the dialectical method by Plato.

Asano (1998) argued that for Plato, mathematics was indispensable to an understanding of the dialectical method. Similarly, Lee argued that the different types of dialectic, including mathematical and Socratic moral dialectics, shared common features with the geometric method (Lee 1935): Upward to the first principles (analysis) and downward to the demonstration/proof (synthesis); emphasis on logical coherence; and an understanding of science as a deductive system starting from a minimum of necessary assumptions. Hence, Lee (1935) argued:

> It thus appears that, in so far as it is mathematical, the object of dialectic is the reduction of mathematics to its first principles; and that the procedure of reduction was suggested by the methods of analysis and synthesis. And so here dialectic has both a mathematical object and origin. Distinct from its mathematical is the moral function of dialectic. Here also we have an intuitive followed by a deductive thought movement. But the object here is definition; and the method not geometrical analysis but Socratic dialectic.

4.2.4 Section Summary and Discussion

The method of analysis and rhetoric played an essential role in Plato's development of the dialectical method and Aristotle's development of the productive sciences. The latter is a description of intentional, purposeful human activity meant to bring about a change in an existing situation through the conception and making of useful and beautiful objects. Aristotle used poetry as a prime example of such an object.

A brief overview of the science of the artificial, its fundamental concepts and reasoning processes describes the contemporary ontological and epistemological view of design. When Simon proposed the science of the artificial, he was influenced by the generally positivist outlook of the scientific community. However, the similarities between Aristotle's productive sciences and Simon's science of the artificial are significant. Both considered design separate from scientific and practical inquiries; both were concerned with agency and change through the creation of useful and beautiful objects or artefacts. Thus, in a way, Aristotle preceded Simon in producing a 'science of the artificial', which he developed based on the two ancient strategies of inquiry.

Buchanan argued that the poetics and rhetoric of Aristotle have always been the underlying concepts and models for the development of the domains of art and production in general. In addition, Buchanan argued that Alexander's conceptualization of design was a dialectical inquiry, the testing of design ideas. However, Buchanan, like Simon, fell short of connecting their conceptualizations of design to the ancient method of analysis.

Applying rhetoric to the conceptualization of design is not as problematic. The use of rhetoric as the basic model is a relatively well-established approach among contemporary design scholars. For example, McKeon and Buchanan (though not Simon) studied the connection between rhetoric and design activity. Thus, it can be argued that the two ancient strategies of inquiry are both still relevant, despite the fact they were developed more than 2300 years ago. Even so, this is a weak justification for relying on the method of analysis and rhetoric as a source of inspiration for the development of a theory of design.

4.3 Two Ancient Strategies of Inquiry

The objective of the previous sections was "to assess whether the method of analysis and rhetoric are suitable candidates for design theorization". Now that their relevance has been established, it is time to better understand those methods. In this section, the essential concepts and principles of the method of analysis and rhetoric are examined. The objective is to reach a clearer understanding of these two strategies of inquiry, investigate their similarities and differences, and determine their relevance to design theorization.

4.3.1 Method of Analysis in Historical and Contemporary Contexts

In ancient Greece, the methods of analysis and synthesis were of critical importance to a small circle of mathematicians and philosophers in the discovery of solutions to geometric problems (Hintikka and Remes 1974). From its inception, the method of analysis has had a great influence not only on geometers and mathematicians, but also on philosophers (e.g., Plato and Aristotle), scientists (e.g., Isaac Newton and Bernard Riemann), politicians (e.g., Abraham Lincoln[6]), and writers (e.g., Edgar Allan Poe) (Carpenter 1867; Cellucci 2013; Hintikka and Remes 1974; Niiniluoto 1999; Ritchey 1991).

The methods of analysis and synthesis have been understood and applied in many ways beyond their original sense and use in the context of geometry, especially in contemporary times (Beaney 2016). Thus, interpretations of these methods and the nature of their relationships have been a subject of recurring debate.

The ancient Greek term for 'analysis' is derived from '*analusis*', the prefix '*ana*' meaning 'up' and '*lusis*' meaning 'loosing', 'release' or 'separation', so that '*analusis*' means literally a 'loosening up' or 'dissolution'. The term was used in ancient Greek geometry and philosophy to denote the finding of solutions or 'dissolving' of problems (Beaney 2016). The ancient Greek term for 'synthesis' is derived from the ancient Greek word '*syntithenai*', from '*syn*' "together" and '*tithenai*' "put, place" (Dictionary 2018). This denotes a combination of two or more entities that together form something new; or alternatively, it denotes the creation of something (McKeon 2003).

Elements and the Treasury of Analysis

Euclid was the first to provide a proper account of 'analysis' and 'synthesis'. Euclid's Elements (300 BC) consists of 13 books that form a collection of definitions, postulates, and propositions (theorems and constructions), including mathematical proofs of the propositions. The books draw on the works of many geometers, most notably, Theaetetus and Eudoxus, who worked closely with Plato and Aristotle (Heath 1956). Heath (1956) described the central idea of Elements as follows:

> But the term element is otherwise used of that into which, being more simple, the composite is divided; and in this sense we can no longer say that everything is an element of everything, but only that things which are more of the nature of principles are elements of those which stand to them in the relation of results, as postulates are elements of theorems.

This passage reflects on the central notion underlying ancient conceptions of methods of analysis, methods of inquiry, and the processes of things: the idea of causalities, composites and their constituent elements, and the relationships between elements.

The challenge of describing the ancient method of analysis stems from the fact that the original ancient sources dealing with the method do not exist, and most

[6] "In the course of my law-reading, I constantly came upon the word demonstrate. I thought at first that I understood its meaning, but soon became satisfied that I did not. [...] At last I said, "Lincoln, you can never make a lawyer if you do not understand what demonstrate means;" and I left my situation in Springfield, went home to my father's house, and stayed there till I could give any proposition in the six books of Euclid at sight. I then found out what "demonstrate" means, and went back to my law-studies.'" (Carpenter 1867)

contemporary discussions are based on secondary materials/sources. These include the interpretations of Pappus and Proclus, as translated, for example, by Heath (1956) and by Hintikka and Remes (1974).

Although the method of analysis was already known to Plato (Menn 2002), Pappus's explanation of the method of analysis, translated into Latin in 1566 (Hintikka and Remes 1974), is considered the only reliable source. Pappus wrote his work six centuries (ca. 300 AD) after Euclid's *Elements* and revealed the "secret" of the Greek geometers, or the "Treasury of Analysis", as follows (Heath 1956):

> The so-called Treasury of Analysis is, in short, a special body of doctrines furnished for the use of those who, after going through the usual elements, wish to obtain the power of solving theoretical problems, which are set to them, and for this purpose only is it useful. It is the work of three men, Euclid, the author of the Elements, Apollonius of Perga, and Aristaeus, the Elder, and proceeds by the method of analysis and synthesis.

The method of analysis was seen as a method for geometric problem-solving with the aim to reveal underlying principles and elements. The three figures mentioned by Pappus, namely Euclid, Apollonius of Perga, and Aristaeus the Elder, laid the foundation for the ancient conceptions of the method of analysis (Heath 1956).

Analysis and Synthesis

In *Mathematical Collection*, Pappus defined 'analysis' as working back from the thing sought (translated by Hintikka and Remes (1974)):

> Now analysis is the way from what is sought - as if it were admitted - through its concomitants in order to something admitted in synthesis. For in analysis we suppose that which is sought to be already done, and we inquire from what it results, and again what is the antecedent of the latter, until we on our backward way light upon something already known and being first in order. And we call such a method analysis, as being a solution backwards.

Pappus's description of analysis defined the principle of working back from complex entities to the simpler, that is, to first principles or axioms from which something can be conceived and demonstrated (Hintikka and Remes 1974). It is the idea of creating chains of end-means relationships towards something admitted, a process for obtaining starting-points for synthesis. Analysis reveals necessary constructions: a point, line, surface, boundary, figure, circle, semicircle, square, oblong, rhombus, rhomboid, or trapezium, as specified in book I of Euclid's Elements; or a solid, pyramid, prism, sphere, cone, cylinder, octahedron, icosahedron, or dodecahedron, as specified in book XI (Netz 2003).

Synthesis progresses in the opposite direction, reversing the steps in analysis, and ends with the demonstration or proof of the thing sought (Beaney 2016; Hintikka and Remes 1974). Pappus defined 'synthesis' (translated by Hintikka and Remes (1974)):

> In synthesis, on the other hand, we suppose that which was reached last in the analysis to be already done, and arranging in their natural order as consequents the former antecedents and linking them one with another, we, in the end, arrive at the construction of the thing sought. And this we call synthesis.

The same methods of analysis and synthesis inspired Aristotle to conceptualize the productive sciences. Aristotle compared human deliberation and making to the structure of the method of analysis. Otte and Panza (1997) described deliberation as a process that starts with the fixation of an end and is concerned with considering the means to achieve it. The end of deliberation is the determination of a (possible) plan to make a thing, implemented in synthesis.

Theoretical and Problematic Kinds of Analysis

Pappus distinguished two kinds of analysis, theoretical analysis and problematic analysis. He described the former as follows (Hintikka and Remes 1974):

> [...] we suppose the thing sought as being and as being true, and then we pass through its concomitants in order, as though they were true and existent by hypothesis, to something admitted; then, if that which is admitted be true, the thing sought is true, too, and the proof will be the reverse of analysis. But if we come upon something false to admit, the thing sought will be false, too.

And the latter as follows (Hintikka and Remes 1974):

> [...] we suppose the desired thing to be known, and then we pass through its concomitants in order, as though they were true, up to something admitted. If the thing admitted is possible or can be done, that is, if it is what the mathematicians call given, the desired thing will also be possible. The proof will again be the reverse of analysis. But if we come upon something impossible to admit, the problem will also be impossible.

Thus, Pappus suggested that in a theoretical analysis the geometer aims to demonstrate a theorem (such as the Pythagorean theorem), and in a problematic analysis, the geometer constructs the figure (such as an equilateral triangle on a given line) (Beaney 2016). Similarly, Proclus makes the following remarks that geometrical inquiry (Beaney 2016):

> [It] is divided into the working out of problems and the discovery of theorems. It calls "problems" those propositions whose aim is to produce, bring into view, or construct what in a sense does not exist, and "theorems" those whose purpose is to see, identify, and demonstrate the existence or nonexistence of an attribute.

However, the two types of analysis have two different interpretations: the first seems to suggest that there are two independent methods of analysis with their own specific structure and logic; the other that the two are complementary. On the basis of the work of Proclus, Hintikka and Remes (1974) argued that theoretical analysis and problematical analysis can be seen as complementary. Likewise, Beaney (2016) wrote:

> Although Euclid's 'Propositions' do divide into theorems and problems, however, these are complementary, since, for every construction we carry out fulfilling the required conditions, there is a corresponding theorem to be proved demonstrating that the construction has the desired properties, and for every theorem, there will be some associated construction to be made.

Beaney (2016) gave an example based on the Pythagorean theorem in a 'problematic form' and argued that solving such a problem would also provide the material to demonstrate the Pythagorean theorem. Thus, in the method of analysis, theoretical analysis and problematic analysis are complementary and involve finding appropriate principles and constructions, a means to solve a problem.

Fundamental Concepts in the Method of Analysis

In David Fowler's words (as cited by Netz (2005)): "Greek mathematics is to draw a figure and tell a story about it." Netz went further: "[the] deductive mathematics grew out of the Greeks drawing lettered diagrams and telling stories by means of them, not only about them." In other words, the geometric diagram and the argument evolve together; one cannot be understood without the other. Netz (2005) proposed that "the diagram is the metonym of mathematics".

According to Proclus, the method of analysis consisted of the following parts, the same for both kinds of problems, the theoretical and problematic (Heath 1956):

- **enunciation (*protasis*)** - as a starting point in the analysis, stating what is 'given' and what is 'sought' (Hintikka and Remes 1974);
    - setting-out – 'marks off' what is given (*dedomena*) and adapts it for use in the investigation;
    - definition or specification – a separate clear statement of the particular thing which is sought or to be proved (*zetoumenon*);
- **construction or machinery** - adds 'what is wanting' to what is given for the purpose of finding what is sought;
- **proof (*apodeixis*)** - draws the required inference by reasoning from acknowledged facts; and
- **conclusion (*sumperasma*)** - reverts to the enunciation, confirming what has been demonstrated. According to Netz (2003), this is where the inductive inference occurs in the geometrical problem-solving sense (repeatability of necessity).

According to Hintikka and Remes, there is also a third type of enunciation, the general enunciation statement, taking a form of 'if-then', but they argued that its usage is not very clear and common in Pappus's terminology (Hintikka and Remes 1974).

Furthermore, Hintikka and Remes (1974) stated that the analytical proof system consists of enunciation (problem clarification) of a theorem or problem, analysis in the broader sense, and synthesis, which begins upon completion of the analysis. The machinery is what corresponds to the analysis, and the proof is what corresponds to the synthesis.

According to Hintikka and Remes (1974) and Heath (1956), analysis and synthesis both consist of two stages, the 'analysis proper' and 'resolution' in the case of the former, and 'construction' and the 'proof proper' in the case of the latter. The different stages of analysis and synthesis can be viewed in terms of parts and wholes or in terms of principles and conclusions. In the first case, analysis moves from wholes to parts, while synthesis arranges parts in wholes. In the second case, analysis proceeds from effects to causes, and synthesis from principles to conclusions (Ritchey 1991).

In the 'analysis proper' it is assumed that the problem is possible and solved, the requirement of the *zetoumenon* fulfilled, and new objects and principles/assertions introduced (Heath 1956). The requirement concerns the interdependencies between the new objects and those parts of the figure which were specified in the enunciation of the problem. A solution principle is then proposed to be proved in the 'proof proper' by reverting the 'analysis proper'.

In the 'resolution' the aim is to show that the objects which were introduced in the 'analysis proper' can be constructed based on the information given in the *dedomena*. 'Resolution' takes the form 'if this is given, that is given' (Hintikka and Remes 1974). The function of the 'resolution' is, first, to show that that the constructions introduced in the analysis proper are independent of the *zetoumenon*, and secondly, to produce a proof of solvability/constructability (*diorismos*). The actual production of the figure is carried out in the 'construction' stage of synthesis.

However, the main characteristic of the resolution is that it does not prove that these constructions solve the problem. This is explained by Hintikka and Remes (1974):

> The interdependencies found in the analysis proper may depend on the *zetoumenon*. What is required in a proof is a 'reverse' deduction from the *dedomena* (and known propositions) through the interdependencies to the *zetoumenon*. This reversibility cannot be assumed without proof. The ancient geometers admittedly sought to prove the reversibility of the deductive (non-constructional) steps, but only in the *apodeixis* of the synthesis. As for the 'resolution', it does not even attempt to prove this reversibility. On the contrary, it accepts without qualification those properties which the geometrical objects introduced in the analysis proper were those properties the objects were assumed to have. What the 'resolution' proves is that these hypothetical objects having these so far hypothetical properties can be constructed on the basis of the *dedomena* alone.

What Hintikka and Remes (1974) argued is that proofs can fail when the 'analysis proper' is not reversible, even if the construction is possible based on the *dedomena*. Constructions can be either irrelevant, insufficient, or either partially or entirely impossible. In this case, the unknown, assumed to be known, must be false too. In the method of analysis, this was known as *reductio ad absurdum* (Niiniluoto 1999).

Thus, in the analysis, one can only establish if the problem is solvable, meaning that certain relationships hold between the different 'given' elements. However, it is only in synthesis, when all the steps in the 'analysis proper' can be converted deductively, that the geometer can show that the problem is solvable

- as soon as the conditions in the 'given' are satisfied. Thus, analysis can only establish necessary but not sufficient conditions of solvability in advance of the synthesis (Hintikka and Remes 1974).

Finally, it is essential to expand on the idea of auxiliary constructions, which are introduced in the 'analysis proper'. Auxiliary constructions are considered a source of unpredictability and the reason for the heuristic nature of the analysis, leading to iterations. Hintikka and Remes described the need for auxiliary lines as follows (Hintikka and Remes 1974):

> [...] figure cannot always be the one which represents the desired theorem. Typically, auxiliary constructions are also needed. They introduce new geometrical objects into this figure. They are needed because the desired proof or construction cannot be carried out without their mediation. In principle, the main non-trivial, unpredictable element of the analytical method lies in these auxiliary constructions. They are therefore heuristically crucial but at the same time heuristically recalcitrant element of the methodological situation.

Two examples to illustrate the structure of the inquiry in the method of analysis are given in Appendix I.

Reasoning Types in Analysis and Synthesis

Analytic and synthetic procedures have been subject to several interpretations. In this section, the intent is not to be exhaustive but to provide an outline of the fundamental concepts based on more modern interpretations of the method of analysis, specifically regarding the different types of inferences. For more detailed discussions, see the works of Holton (1998) and Codinhoto (2013).

The mainstream view of analysis in contemporary conceptualizations is that it is 'breaking something down', i.e., it is the resolution of complex entities into simpler elements (Beaney 2016). Known as the decomposition view of analysis, it is the study of geometrical objects and their dependencies; i.e., configurations of given and sought elements (e.g., lines, angles, and points) and the relationships between them. According to Hintikka and Remes (1974), this is the dominant type of problem-solving in the 'resolution' stage.

According to the another interpretation of Pappus's description of the method of analysis, analysis refers primarily to the working back from more complex entities to the means by which something can be conceived and demonstrated. Beaney (2016) called this a regressive conception of analysis, and defined it as "the process of identifying the principles, premises, causes [and] means [by] which something can be derived or explained". This is supposed to be the dominant type of problem-solving in the 'analysis proper' stage (Hintikka and Remes 1974). Furthremore, Niiniluoto (1999) argued that sometimes regression can be an abductive inference.

Beaney (2016) and Codinhoto (2013) suggested that there is also a transformative/interpretive dimension to analysis. Transformation, which typically takes place before other types of analysis, including regression and decomposition, involves the translation of the initial description of a 'phenomenon' into a 'correct' logical form, e.g., textual problems into algebraic/geometric problems. In the language of the configurational conceptualization of the method of analysis, this is the dominant type of problem-solving expressed in the 'enunciation' (Hintikka and Remes 1974).

These conceptions of analysis and types of reasoning are not conflicting but rather, complementary. For example, Polya (2014) described mathematical problem-solving in four easy to understand steps: understand the problem, devise a plan, do the plan, and look back. 'Understand the problem' requires specification, a definition of the problem, the given and the thing sought; i.e., transformation/interpretation and decomposition are the key types of reasoning in this step. 'Devise a plan' involves recognition of the pattern, working backward, guessing and testing, breaking the problem down into smaller problems; i.e., it involves the regressive and decomposition types of reasoning.

Mäenpää (1997) described the different types of reasoning in synthesis. Synthesis as a procedure involves putting together the given objects to achieve the thing sought, leveraging the interdependencies uncovered in the analysis. In other words, it involves compositional reasoning and an assembly operation (Kroll and Koskela 2015). In synthesis, these candidate constructions are also tested to deduce their consequences. Ritchey (1991), drawing from an analogy with the method of analysis, described testing as a procedure to determine the laws of interaction between parts and their response to stimuli through deduction (i.e., the inference of effects from given causes). Netz (2003) added to this list inductive analogy based on the implicit repeatability of moves in the demonstration.

In summary, analysis establishes a conceptual framework (Codinhoto 2013), the so-called machinery defined by Hintikka and Remes (1974). This creates a baseline for synthesis to verify the propositions (McKeon 1968). In case of failure to prove or demonstrate the theorem or problem in synthesis, this process leads to a new iteration through analysis back to synthesis (Ritchey 1991).

General Characteristics of Analysis and Synthesis

Although a description of the three types of reasoning can provide guidance about which method to apply and when to apply it, it does not provide an algorithm for solving problems. This was already recognized by Aristotle, Descartes, and Leibniz (Holton 1998).

Analysis can be either logical or heuristic (Timmermans 1999), depending on the focus and starting point. In the logical view of analysis, one starts from an unknown thing "as if it were known" and "works backward" to the end of the analysis, something admitted. However, if one starts from something admitted to be known and ends with something known in the analysis, this is not a discovery. One cannot discover something what was already known. This is also known as Meno's paradox (Beaney 2016). Thus, analysis, from the view of logic, can lead only to the verification of the status "known" in synthesis (Timmermans 1999).

McKeon (1968) defined verification as an "investigation of grounds in fact, probability, or scientific law for descriptions or explanations". Moreover, "verification involves the analysis of the relations of consistency, relevance, and appropriateness of statements in inference; it is demonstration by establishment of applications in things" (McKeon 1968).

Analysis also has a heuristic meaning, where one assumes something given and aims to determine the conditions and constructions necessary to prepare a figure; i.e., analysis is a process of discovery (Timmermans 1999). As Hintikka and Remes (1974) argued, what makes analysis heuristic in nature is the introduction of auxiliary constructions. Some lines of thought in analysis can lead to something impossible (*reductio ad absurdum*). Thus, there is no guarantee of finding a solution in the first attempt, meaning that trial-and-error is needed (Polya 2014).

The recognition of 'patterns' and the introduction of new objects and relationships as auxiliary constructions is dependent on the experiences of the problem solver. Pólya (1990) argued that the capacity to observe and propose a definition for a pattern and its subcategories could be attributed to intuition. Descartes also agreed that intuition is part of the method of discovery (Holton 1998).

In the case of synthesis, the relationship between analysis and synthesis needs to be clarified; i.e., whether analysis and synthesis are two separate, albeit complementary, methods or together constitute one method of analysis-synthesis. As discussed above, there is not always a need for synthesis, i.e., it is unnecessary when analysis leads to something impossible. However, one always needs synthesis if the analysis has revealed the necessary conditions and constructions for a demonstration/proof, i.e., the objects, properties, and relationships between these objects and properties (Hintikka and Remes 1974).

In the theoretical type of analysis, the end of synthesis is proof of the theorem; in the problematic type of analysis, it is the demonstration that something sought can be constructed based on the thing given and new objects and relationships introduced. McKeon (1968), who studied the method of analysis and sought to develop a philosophy for it, defined "demonstration as a process of proof from immediate or axiomatic premises in logic, mathematics, or science, or demonstration that something can be constructed".

However, can synthesis be conducted without analysis? Mäenpää (1997) argued that it is possible to have synthesis without analysis by proceeding from objects assumed to be given to the ones sought and then demonstrating that the conditions are met through induction.

4.3.2 Rhetoric in Historical and Contemporary Contexts

In the second half of the 20th century, rhetorical as well as dialectical theories of argumentation witnessed a remarkable revival (Van Eemeren and Houtlosser 2003). These methodological concepts have been used to inform the development of different conceptualizations in various disciplines, including design (Buchanan 2009). In this section, the intent is to lay out the philosophy and practice of rhetoric, beginning with a study of its Aristotelian roots.

Origins, Definitions and Applications

Rhetoric as a discipline emerged in connection with the need of citizens to speak for themselves and be persuasive in the courts of law in ancient Greece (Kennedy 2007). Aristotle was the first to provide a thorough description of the art of rhetoric as *techne* in his book *Rhetoric* (Herrick 2015). For Aristotle, rhetoric was "...the faculty (*dunamis*: capacity, power) of observing in any given case the available means of persuasion" (Kennedy 2007). Rhetoric was a discipline for developing persuasive communication, but also the formal art of studying such communication. Every persuasive utterance or piece of writing is a rhetorical act. In Aristotle's fundamental treatise on the subject, he deemed it a counterpart to dialectic (Rapp 2016): "what dialectic is for the (private or academic) practice of attacking and maintaining an argument, rhetoric is for the (public) practice of defending oneself or accusing an opponent".

McKeon et al. (1998) described rhetoric as a master discipline, "a universal and architectonic art". Rhetoric is present everywhere, and rhetoric as an architectonic art gives structure to other arts and disciplines (McKeon et al. 1998). Rhetoric is the study of organizing and employing language or any subject matter effectively. Kennedy (2007) defined rhetoric as "the energy inherent in emotion and thought, transmitted through a system of signs, including language, to others to influence their decisions and actions." Herrick (2015) defined rhetoric as an art of "the study and practice of effective symbolic expression" and a type of discourse: "goal-oriented discourse that seeks, by means of the resources of symbols, to adapt ideas to an audience". Rhetoric as a discipline is not limited to words and speech but applies to any argumentative discourse (rhetorical syllogism is known as enthymemes), no matter the subject matter and medium (Buchanan 1985).

Aristotle proposed three genres of rhetoric (Kennedy 2007): if a judge of past actions, the species is judicial; if a judge of future action, the species is deliberative*;* if an observer of the speech, not called on to take action, the species is epideictic. These are further characterized according to whether or not the audience is a judge; whether or not the audience is able to take specific action as a result of being persuaded; and the time with which the genre is concerned (Kennedy 2007). Herrick (2015) provided a contemporary interpretation of the three genres of rhetoric. Judicial (*forensic*) oratory reconstructs the past by inferring a plausible hypothesis from evidence. Deliberative oratory is concerned with actions (future-oriented), what should be done, and deals with questions of the best use of means. Epideictic (ceremonial) oratory deals with issues of praise (*epainos*) and blame (*psogos*) to demonstrate what is honorable (*kalon*) and to influence public values.

Each of these three genres has a particular end, the principal issue with which they are concerned (Herrick 2015):

> [...] the end of judicial rhetoric is justice; the end of deliberative rhetoric is in the best interest of the audience; and the end of epideictic rhetoric is praise or blame of the subject.

Common to these definitions is the idea of using a medium, symbol systems, as 'productive' assets for communicating meaning. For example, Herrick (2015) described architecture as a rhetorical art, stating that the lines, shapes, and materials are used symbolically to communicate meaning and achieve persuasion. Thus, rhetoric is an art of creative and persuasive communication forming a universal system for the setting, content, aim, and means (Joost and Scheuermann 2007).

Rhetorical Situation and Common Ground

A rhetorical discourse is intentional and contextual; the intended audience affects the selection of means. The audience as a universal concept in rhetoric does not only include 'others', but it does also include, as Herrick (2015) described it, a "oneself". This means the inner voice of the person arguing/debating with his or herself. As such, rhetorical activity is present in many aspects of human agency.

Rhetorical discourse starts with an opportune occasion for speech (*kairos*), i.e., when a given context for communication both calls for and constrains one's speech (Burton 1996). A rhetorical situation (Dave et al. 2015; Herrick 2015) consists of the rhetor, the medium (typically speech in classical rhetoric), and the audience. A rhetor must take into account the context of a given place and time and consider the opportunities for words to be useful and appropriate to that moment. The starting point of rhetorical discourse is *endoxa*[7] (common ground), values, facts, and presumptions shared by the rhetor and the audience (Dave et al. 2015). This means the rhetor must adapt to his or her audience (Herrick 2015).

Rhetorical discourse is a relationship, interaction between the rhetor and his/her audience, brought together through a variety of objects (medium) of communication. This link is best described by Burton (1996): "the central rhetorical principle requires rhetor's words and subject matter be aptly fit to each other, to the circumstances and occasion (*kairos*), the audience, and the speaker." Thus, inspired by Joost and Scheuermann (2007), **Figure 10** is proposed to illustrate the fundamental concepts and their relationships.

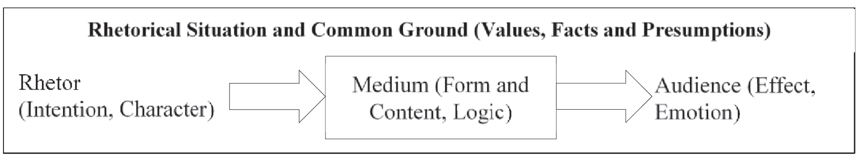


Figure 10. Rhetorical concepts and their relationships.

Arguments are Subject to Appeals

According to Aristotle, arguments are the glue for connecting the elements of speech to facilitate active engagement between the rhetor and the audience. Three types of rhetorical appeals, or persuasion strategies, are used in the construction of arguments to support claims and respond to opposing arguments. A good argument generally uses a combination of all three appeals to make its case (Buchanan 1985; Herrick 2015; Weida and Stolley 2013):

[7] Amossy (2002): "Aristotle described endoxa as what appears manifest and true to all, or to most of the people, or to the wise […] Doxa […] nothing to do with Truth. Its impact derives from its being accepted […] guides decisions and actions in human affairs […] rhetoric, feeding on doxa, is needed in all matters where there can be no absolute Truth, namely, in human affairs."

- ***Ethos*** - is an appeal to morals (values), concerned with the means to convince someone of the character or credibility of the persuader (including individual, general public, movement, or culture). Thus, it is the character of the speaker/writer made evident in a medium, to achieve a special relationship with the audience by giving the appearance of trustworthiness.
- ***Logos*** – is an appeal to logic, the use of reason to persuade an audience; i.e., the use of the integrity and clarity of an argument (inductive and deductive reasoning) as well as the logic of evidence and reasons.
- ***Pathos*** - is an appeal to the emotions and social circumstances of the audience.

These three appeals are employed in all three genres of rhetoric (judicial, deliberative and epideictic), but certain strategies of argument are used in one more than the other (Herrick 2015).

Aristotle proposed two types of strategies of arguments or *topoi* in rhetoric, special strategies related to a specific type of rhetoric and common strategies relevant to all types of rhetoric (universal strategies of argument) (Kennedy 2007). These unique and common strategies were provided as guidelines not only for inventing or discovering arguments but also for thinking productively about them. The *topoi* can also be thought of as different viewpoints from which to survey an issue or identify a weak argument. Aristotle's *Topics* and *Rhetoric* contain about a hundred different *topoi* for understanding dialectical arguments or the persuasiveness of public speech (Kennedy 2007).

Rhetorical Inquiry

In general, two types of processes have been described in the context of rhetoric, namely invention and judgment. These processes have opposing yet complementary functions. Joost and Scheuermann (2007) described these effect-oriented processes as a loop of rhetorical production (rhetor-medium-audience, see **Figure 10**) and reception/analysis (the opposite process of audience-medium-rhetor). In other words, these processes can be understood, respectively, as the process of creating persuasive communication and the process of evaluating such communication.

Aristotle described invention as a method to guide a rhetor's discourse and a practice that could be studied and taught (Lauer 2004). According to McKeon (1966), "method is needed in the invention to define the question and to order the data pertinent to it". Lauer described invention, the first stage in Aristotle's rhetoric, as the rhetor's examination of alternatives (Lauer 2004):

- different ways to begin and to explore situations;
- diverse ideas, arguments, appeals, and subject matters for reaching new understandings and for developing and supporting judgments, theses and insights; and
- different ways of framing (re-framing) and verifying these judgments.

Although invention can occur throughout the entire process of rhetorical discourse, it emerges most intensely in the early phases of the rhetorical process.

Rhetoric as a method was devoted to finding ways (genre, form, and arrangement) to have an impact on an audience (Lauer 2004). Thus, invention is the art of discovering arguments and new things.

Judgment is the testing of the ideas and arguments established during the invention stage. McKeon (1966) defined judgment as "the art of testing arguments, proving conclusions, and verifying statements". Further, McKeon (1968) defined the content of judgment as follows:

> Judgment takes its meanings in a context of definition and opposition. It is an estimation of persons in the light of their actions and accomplishments and of things in the light of their qualities and effects, with the possible influence of sensibility and taste [...] When judgment becomes a universal method, it is not restricted to subject-matters under the jurisdiction of courts of law or under the scrutiny of aesthetic criticism but determines all subject matters.

Concerning the development of persuasive speech, classical treatises on rhetoric provide descriptive, explanatory and prescriptive treatments of oratory. Among the most well-known is a description of the stages of preparing and delivering a speech (Burton 1996; Kennedy 2007; Koskela and Ballard 2013):

- ***Inventio*** (invention) involves finding or discovering the topics of a speech, as well as determining the nature of the case, selecting the intention, and analyzing the audience.
- ***Dispositio*** (arrangement) is about organizing the topics into a speech, i.e., parts into a whole. For example, Cicero proposed an arrangement of classical oration (Burton 1996): introduction (*exordium*), statement of facts (*narratio*), division (*partitio*), proof (*cofirmatio*), refutation (*refutatio*), and conclusion (*peroratio*). Furthermore, Cicero aligned certain rhetorical appeals with specific parts of the oration (Herrick 2015): *ethos* in the introduction; *logos* in the statement of facts, division, proof, refutation; and *pathos* in conclusions.
- ***Elocutio*** (style) refers to the artful expression of ideas using different rhetorical methods and devices as a means to deliver the topics.
- ***Memoria*** (memory) is connected with the fact that in Antiquity, speeches were mostly delivered from memory. Often mnemonic devices, external representations, were used to help remember the speech.
- ***Actio*** (delivery) refers to the use of gestures, facial expressions, and voice during the delivery of the speech.

In classical rhetoric (Herrick 2015), each of the five stages in the development of a speech has a field of study dedicated to it. In the invention stage, the speaker seeks arguments which are appropriate to the subject matter. These are then organized in the arrangement (disposition) stage. This is followed by choice of style, memorization, and delivery. The fields of knowledge mapped out for these different stages of the process can be found in various art genres; e.g., architecture, acting, and literature (Joost and Scheuermann 2007; Kennedy 2007).

4.3.3 Features of the Method of Analysis and Rhetoric

The features of the method of analysis and rhetoric are briefly addressed based on the articles by Koskela et al. (2014) and Koskela and Ballard (2013) on the proto-theory of design and the two pillars of design conceptualization. However, three additional, yet significant features are identified: persuasion strategies, the use of representations/models, and a conceptualization of the strategies of inquiry from the perspective of both an individual and the collective.

The starting and end points of the method of analysis differ from those of rhetoric. In the method of analysis, the start and end points are considered qualitatively different. In geometry, the problems are assumed to be given, what is given and sought, or can be objectively defined (problem clarification). At the start of analysis, the 'thing sought' is assumed to be given and known, and the end of analysis is something admitted, already known. However, a given geometrical problem can be partially or wholly underspecified (Netz 2003). Hence, analysis can also lead to something impossible: the unknown assumed to be known, must be false - *reductio ad absurdum* (Niiniluoto 1999). Synthesis begins after analysis and demonstrates whether the 'thing sought' exists or not. In rhetoric, the starting point is the problematic situation (*kairos*): time and place, subject, common ground, and audience. The objective of rhetorical discourse is to change a given situation. The end is judgmental, concerned with whether the audience was persuaded or not (Burton 1996; Kennedy 2007). Thus, the different start and end points represent different states of knowledge about the 'thing sought'. In analysis, the outcome of synthesis is a geometric figure as a solution, in rhetoric, persuasion of an audience.

In the method of analysis, two different types of analysis have been defined, theoretical analysis and problematical analysis. In the first, analysis proceeds from effects to causes, and synthesis from principles to conclusions; in the second, analysis moves from wholes to parts, while synthesis arranges parts into wholes. According to this view of the method of analysis, analysis and synthesis both consist of two stages: the proof of a theorem and construction of a figure. Thus, these are not mutually exclusive, but complementary modes of geometrical problem-solving. Polya (2014) proposed another interpretation: the analytic process corresponds to the 'problem to find', and the synthetic process to the 'problem to prove'. A problem-solver can be problem- or solution-oriented, depending on the problem (simple or complicated) and the experiences and skills of the problem-solver. In rhetoric, there is no clear distinction between problem or solution approaches; instead, the focus is on the whole and co-evolution of the problem and solution.

In the method of analysis, the stages are divided into problem clarification, the analysis proper, and resolution in the analysis part, and construction, the demonstration/proof proper, and conclusion in the synthesis part. In rhetoric, the stages include invention, arrangement, style (implementation), memorization, and delivery/judgment. The memorization stage is characteristic of the oral arts of rhetoric. In the method of analysis, the focus is on investigation of the necessary conditions for problem-solving, i.e., analysis of the ends-means relationships between elements and their properties. The types of reasoning involved include transformation, regression, and decomposition in the analysis part; and composition, deduction, and induction (in a geometric sense) in the synthesis part. The method of analysis has always been tightly coupled with the making of a geometric figure (Netz 2003). Therefore, synthesis has a dual nature; in addition to subjective activities, synthesis also involves objective ones: assembly, testing, and verification of geometric figures. In rhetoric, both inductive and deductive reasoning (and perhaps abductive reasoning as well) are used to develop arguments, appealing to logic. Operations in rhetoric include style (implementation), memorization, and delivery.

In the method of analysis, since analysis and synthesis have complementary functions, even mirroring each other, there is a unity of the stages in both directions: enunciation-conclusion, discovery-proof, and resolution-construction. In rhetoric, this relationship is more complicated and has two interpretations. According to the first, judgment occurs during the invention stage (judgment by the rhetor) and during the delivery stage (judgment by the audience). According to the second, judgment occurs at nearly every stage of rhetorical discourse, including invention, arrangement, style, and delivery, with the exception of the memorization stage.

Argumentation in rhetoric is subject to different appeals: *logos* (persuasive argument), *ethos* (source of the message), and *pathos* (emotions). In the method of analysis, the focus is entirely on the development of logical arguments and constructs. The method of analysis and rhetoric thus overlap in their use logic. In the method of analysis, the strategies of inquiry in the analysis part are heuristic and iterative but determined in the synthesis part. In rhetoric, the development of argumentative speech is subject to continuous judgment and is, therefore, iterative.

Creativity in the method of analysis is in the discovery and demonstration of the principles and means for solving a problem; in rhetoric, it is in the invention of topics, the composition (arrangement) of the message, and the expression of topics in oral speech (style). In the method of analysis, the relationships between the whole and parts are tractable and straightforward in both analysis and synthesis; in rhetoric, they can be rather intractable and complex. In the method of analysis, evaluation is in the demonstration of the constructed figure or proof of the theorem at the end of the synthesis. In rhetoric, evaluation is the judgment by the audience (including oneself). The method of analysis and rhetoric, like the productive arts, are concerned with the making of an object, or its representation: the geometric figure in the method of analysis, and linguistic elements and persuasive gestures in rhetoric. In the method of analysis, the focus is on the internal argumentation and communication of an individual, while in rhetoric, in addition to rhetor, there are two other types of audiences: direct and wider audiences of interest. Although rhetoric is concerned with the discourse of an individual, the emphasis is on communication and collaboration with a broader audience. The summary of comparision is presented in **Table 6**.

Table 6. Comparison of the method of analysis and rhetoric regarding their fundamental characteristics (partially adopted from Koskela et al. (2014) and Koskela and Ballard (2013)).

Characteristics	Method of Analysis	Rhetoric
Starting and end points	Given problem (assumed): enunciation of something 'given' and 'sought'; demonstration/proof (a geometric figure)	Given situation (time and place, audience, and common values; needs to be studied); persuasion of the audience
Types of analysis	Problematic: problem to find; theoretical: problem to prove	Problem and solution are co-evolving
Stages	In analysis, clarification of the problem, the analysis proper, and resolution; in synthesis, construction, demonstration/proof, and conclusion	Invention, arrangement, style (implementation), memory, and delivery
Modes of reasoning	Necessary reasoning (certain and universal)	Plausible reasoning (probable and particular)
Types of reasoning	Transformation, regression (abductive), and decomposition in analysis; and composition, deduction, and induction in synthesis	Induction and deduction in logos
Types of external activities	Assembly, testing, and verification	Style (implementation), memorization, and delivery/judgment
The unity of the two directions	Enunciation-conclusion, discovery-proof, and resolution-construction	Invention-judgment, arrangement-judgment, style-judgment, and delivery-judgment
Strategies of persuasion (appeals)	Logic	*Logos*, ethos, *pathos*
Strategies of reasoning	Heuristic and iterative in the analysis; determined in the synthesis	Iterative
Creativity	Discovery and demonstration of the principles and means for solving a problem	Invention of topics, composition of topics (arrangement), expression of topics in oral speech (style)
Whole and parts	Simple, tractable	Complex, intractable
Evaluation	Demonstration by construction of a figure or proof of a theorem	Judgment by the audience
Representations	Symbolic systems (geometric objects and relationships for problem-solving)	Symbolic systems (linguistic elements and gestures for persuasion)
Individual and collective	The internal argumentation of an individual	Communication as a means for collaboration

4.3.4 Analogous Features in Current Design Theories

This sub-section summarizes the results of the present investigation into whether key features of the method of analysis and rhetoric are similar to or analogous with key features of the current methodical and theoretical landscape of design. In the previous sub-section, on the basis of a study of the method of analysis and rhetoric in ancient and contemporary contexts, 14 key features were identified. In Appendix II, these key features of the method of analysis and rhetoric are compared to similar or analogous ones in current design theorization. In each sub-section, the given feature of the method of analysis or rhetoric is summarized, and then the feature is compared with its counterpart in the seminal works of current design literature.

The present investigation revealed that current literature on design theorization is rich in its breadth and depth. The features of the ancient strategies of inquiry do have counterparts in contemporary design conceptualizations. That is, although the ancient methods of inquiry have not directly influenced contemporary conceptualizations of design, their features have been re-invented to be part of the latter. Since the first design methods movement, the underlying ambition of the field has been to describe the activities and cycles of the design process and the outcomes of this process. The influence of philosophical pluralism becomes evident in the comparison. Studies have focused on either a description of emerging structures of design activity, human experiences, and the product, or prescriptions for improving the dynamic and changing nature of design practices.

Although the comparison of the features of the method of analysis and rhetoric to similar features in design literature cannot be exhaustive, it provides initial evidence that the two strategies of inquiry can be considered underlying models for design conceptualization.

4.4 Design Theory and The Two Strategies of Inquiry

The previous sections addressed the characteristics and elements of a unified theory of design, Aristotle's productive sciences, and key features of the method of geometric problem solving and rhetoric. In this sub-section, the objective is to investigate whether the first or the second or a combination of the two can form a proper basis for the development of a unified theory of design. The two are compared with respect to the design theory elements identified in sub-section 4.1.3, as these provide a common ground from which to understand the scope and phenomena that these two strategies address.

Table 7 summarizes the results of the comparison of features of the method of analysis and rhetoric according to the six elements of design theory, defined in sub-section 4.1.3. Before stating the similarities or differences between the two strategies of inquiry, it is important to note that the two are by definition design theories. The purpose and scope of the method of analysis are the solving of geometrical problems (verb) and discovery of geometrical solutions (noun): the structure of propositions (theorems and constructions). Two kinds of analysis have been distinguished: theoretical analysis and problematical analysis. The purpose and scope of rhetoric is the development of persuasive communication and the study of such communication. Three genres of rhetoric have been distinguished on the basis of fundamental characteristics of the rhetorical situation: the judicial, deliberative and epideictic.

The method of analysis has been used primarily to conceptualize object-oriented human activity in the context of geometrical problem-solving. Rhetoric has been used to conceptualize subject- and object-oriented activities in the context of persuasive communication (human interactions). Therefore, the constructs (factors) addressed in the method of analysis include definitions, postulates, causalities (cause and effect), and relationships (wholes to parts) of geometrical figures. In rhetoric, constructs include the given situation, common ground, the rhetor (intention and character), the medium of communication (content, form, and logic), and the audience (effects and emotions) of persuasive communications.

In the method of analysis, the strategies and types of reasoning and external activities of analysis and synthesis have been defined to describe the relationships between different factors, i.e., how the methods of inquiry influence the processing of things. In rhetoric, the argument (subject to character (*ethos*), logic (*logos*) and emotion (*pathos*)) is the common denominator underlying the different factors of persuasive communication.

Both strategies of inquiry define different stages, the method of analysis for geometrical problem solving, rhetoric for developing persuasive communication. In the method of analysis, three stages in both analysis and synthesis (unity in opposing directions): problem clarification, the analysis proper, and resolution in the analysis part; construction, demonstration, and conclusion in the synthesis part. In analysis, the different stages bridge the different states of geometrical problems and solutions, progressing from what is given and sought at the end of the problem clarification to solution principle(s) at the end of the analysis proper and from there to constructions (solution embodiments) at the end of the resolution stage. Synthesis progresses in the opposite direction. The three states of the artefact, assembly, demonstration, and conclusions, are connected by the three stages of synthesis, construction, demonstration, and conclusion.

In the method of analysis, testable propositions of theorems and constructions are made in the analysis and demonstrated/proven in the synthesis. In rhetoric, arguments of topics, arrangements, and expressions of arguments are developed and eventually judged by the audience. In the method of analysis, knowledge of existing proven theorems and constructions of geometry and logic are used to justify and explain things. In rhetoric, knowledge of the common ground (*endoxa*: values, beliefs, and presumptions) and rules of logical argumentation act as the starting point for the development of persuasive communication. Thus, based on the brief description provided of the two strategies of inquiry, it can be inferred that the two are related. Both are concerned with the making of an object (geometric figure or speech), but are different strategies of inquiry.

Table 7. Comparison of the method of analysis and rhetoric according to the elements of design theory.

Elements of (Design) Theory	Method of Analysis	Rhetoric
Purpose and scope (boundaries)	Strategy for solving and discovering solutions for geometric problems (Two kinds: theoretical and problematical)	Strategy for persuasive communication and studying such communication (Three kinds: judicial, deliberative and epideictic)
Constructs (factors)	Definitions, postulates, causalities (cause and effect) and relationships (wholes and parts)	Given situation, common ground, the rhetor (intention and character), the medium of communication (content, form, and logic), audience (effects and emotions)
Principles of form and function (relationships)	Strategies (heuristic, iterative, and determined) and types of reasoning and external activities in analysis and synthesis	Arguments subject to character (ethos), logic (logos), and emotion (pathos)
System (product or process) states/stages	Object: Given and sought, solution principles, and constructions in analysis; assembly, proof, and decision in synthesis Process: Problem clarification, analysis proper, and resolution in analysis; and construction, demonstration, and conclusion in synthesis	Process: Invention, arrangement, style (implementation), memory, and delivery
Testable propositions or arguments	Propositions: theorems and constructions	Arguments (topics, composition, and expression) and enthymemes
Justificatory/Explanatory knowledge	Proven theorems, constructions of geometry, and logic	Common ground (*endoxa*: values, beliefs, and presumptions) and rules of logical argumentation

The majority of contemporary design scholars have either not been interested in or failed to consider the method of analysis and rhetoric as fundamental models for developing a theory of design (see section 4.2). It is argued that the method of analysis leans towards the positivist view of conceptualizing design activity, and rhetoric towards the constructivist view. Historically, these perspectives, either positivist or constructivist, technical or social, were considered separate and incompatible, as evident in the division of design concepts into different camps. Here, it is contended that the two must be considered complementary, and as was argued in Chapter 3, pragmatic philosophy makes it possible to integrate the two strategies of inquiry.

What emerges is a conceptual framework: design addresses two fundamental phenomena, the interpretative and causal phenomena. Instead of demarcating the problems hierarchically as was proposed by Simon (1981), descending from the most complex problems to problems of formal scientific inquiry, it is argued that all problems and solutions of design and designing possess varying degrees of interpretation and causality. This is apparent in the most extreme cases of geometrical problem solving and rhetorical oratory. Netz argued that even in ancient Greece, geometrical problem solving was influenced by issues of the rhetorical arts (Netz 2003). Similarly, in the art of rhetoric, arguments appealing to logic have been considered a significant element of persuasive speech. Analogically, Bucciarelli argued that even in the most typical engineering design cases, there are issues that can be understood only in the social context (Bucciarelli 1994). **Figure 11** depicts the varying proportions of interpretation and causality in different design problems.

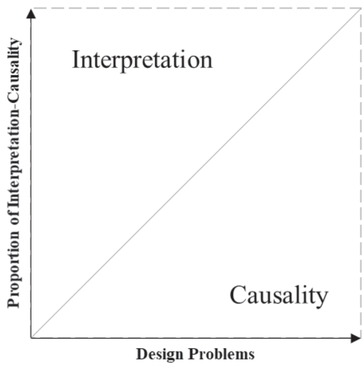


Figure 11. The varying proportions of interpretation and causality in different design problems.

4.5 Chapter Summary and Discussion

In this chapter, the intent was to investigate the requirements and criteria for developing a theory of design, justify the importance of the method of analysis and rhetoric in design, study the central concepts and principles of the method of analysis and rhetoric, and look for analogous or similar features in contemporary conceptualizations.

In order to develop a unified theory of design, consistent and clear definitions of design and designing need to be developed. Design as a situated human activity is about change. Designing involves both internal activities (a minimum of one non-routine activity) and external activities, subjective analytical and synthetic methods of inquiry, and the objective synthetic processes of things (see 3.1.4). Designing is embedded in or influenced by social processes. Design theory should at a minimum contain six elements: (1) purpose and scope, (2) constructs, (3) principles of form and function, (4) artifact mutability (i.e., system (product or process) states), (5) testable propositions and arguments, and (6) justificatory knowledge. These together with specific criteria ('consistency', 'viability', 'elegance', 'philosophical relevance for design', and 'theoretical relevance to design') form the requirements for a theory of design and its development.

Aristotle was inspired by the method of analysis and rhetoric to develop the productive sciences, known as a productive act, or production in general: an intentional and purposeful human activity for conceiving and making useful and beautiful objects. However, the majority of contemporary design scholars have either neglected or failed to make this connection with the two ancient strategies of inquiry. When the features of the method of analysis and rhetoric were compared with contemporary conceptions of design, many correspondences were identified. Thus, it was argued that the two ancient strategies of inquiry are still relevant.

In section 4.4, concepts and principles were mapped to the six elements of design theory addressed in sub-section 4.1.3. It was inferred that the two strategies of inquiry (the method of analysis and rhetoric) are related, as both are concerned with the making of an object (a geometric figure or speech), but are different strategies of inquiry. The method of analysis explicates the positivist view of conceptualizing design activity and rhetoric the constructivist. While these views have been considered separate and incompatible, arguably they should in fact be considered complementary.

Pragmatic philosophy has made it possible to integrate the two. Integration is justified by the nature of design solutions and problems, which possess varying degrees of interpretation and causality, evident in the extreme cases of geometrical problem solving and rhetorical oratory. Thus, a conceptual framework for the construction of a new design model was created and justification for the application of the two ancient strategies of inquiry was given.

I am never content until I have constructed a [...] model of the subject I am studying. If I succeed in making one, I understand; otherwise I do not.

Lord Kelvin (William Thomson)

5. Construction of a New Design Model

In this chapter, a new design model incorporating the causal and interpretative conceptions of design activity is constructed. The intent is to answer the question of what kind of new design model can be synthesized on the basis of the method of analysis and rhetoric. The construction of the new design model is carried out in three phases, where the first two phases correspond to the descriptive part and the third to the prescriptive part of the construction. Section 5.1, covers concepts related to the philosophical framing: the fundamental ideas of designing, the underlying metaphysical, ontological and epistemological concepts, which can be categorized either as analytic or synthetic, are defined. Sections 5.2 and 5.3 encompass ideas related the method of analysis, and rhetoric: the philosophical framework is further developed on the basis of the concepts and principles of the method of analysis and rhetoric. In the third phase (section 5.4), a new prescriptive design model is constructed. Finally, a chapter summary is provided in section 5.5.

5.1 Philosophical Framing for a Design Model

There are three points of departure for the synthesis of philosophical concepts. The first is the broad conceptualization of design as human activity involving the situated subject- and object-oriented mental and external actions and operations of designers (see section 3.1). Designing can be more broadly defined as non-routine individual internal activity, potentially pursuing novelty (see sub-section 4.1.4). The second is the framing of design activity by pragmatist philosophy, enabling the integration of two different perspectives: a positivist perspective focusing on the solution domain and a constructivist perspective focusing on the problem domain (sub-section 3.3). The third is the supposition that design covers two different phenomena, both the causal and interpretational conceptions of design, as every design process needs to address both (section 4.4).

Design activities occur at the intersection of ontological and epistemological dimensions. Ontology is concerned with different categories of reality, in this case, the categorization of design activities (situated subject- and object-oriented). Epistemology is concerned with the creation, application, and justification of design knowledge. It is proposed that ontology and epistemology form a two-dimensional plane (see **Figure 12**).

Mental and external situated subject- and object-oriented activities operate in three different contexts: mental models, conceptual (symbolic) models, and material systems (sub-section 3.1.2). In the context of mental models, design progresses through analysis, while in conceptual models and material systems, design progresses through synthesis. The three categories of activities are divided into two rows in Figure 12, one row representing subject-oriented activites, the other object-oriented activities. The top row represents the interpretative dimension of the framework, i.e., the transition from sensory experiences to perceptions and conceptions, (Stevens 2012); the bottom row the causal dimension of the framework, i.e., the transition from problem-solving to simulations/representations (in the mind or in symbolic systems) and actions involved in the making of the artefact. The result is a three by two matrix representing the ontological categories of human activities: situated subject- and object-oriented mental and external activities.

The epistemological dimension is concerned with the movement between different activities used to create, apply and justify (to verify and validate) knowledge. **Figure 12** depicts an intermediate product to demonstrate and summarize these concepts. Although this organization of different types of activities seems structured, in reality, they occur in an intertwined manner.

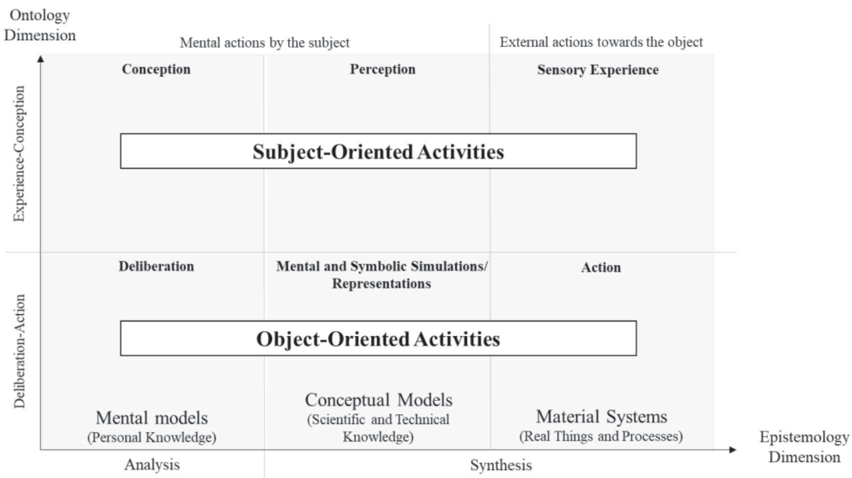


Figure 12. Proposed philosophical framework for design conceptualization.

For this thesis, a simplification of the philosophical framework depicted in **Figure 12** is proposed. As the subjective (mental activities) synthesis and objective (external activities) synthesis proceed in an interwoven manner, given the dual nature of synthesis, they are merged for all practical purposes (sub-section 4.3.3). In **Figure 13**, the conceptual models domain (scientific and technical knowledge) and material systems domain (real things and practical processes) are, accordingly, combined.

Furthermore, as argued by Simon (1981), the vertical split describes the interrelationship between the artefact's system (solution domain) and its environment (problem domain) (sub-section 4.2.2). Lurås (2016) proposed dividing the design situation into three nested sub-systems: 'the system we design within', 'the system we design for' and 'the system we design' (see Appendix II). According to this model, the interpretational dimension of designing related to the artefact's environment can thus be divided into two nested systems, 'the system we design within' and 'the system we design for'. The former corresponds to the part of the world that defines the social, economic, and environmental context and purpose relevant to a particular design project. The latter is the immediate, interactive environment of the newly planned artefact (Goldhagen 2017): users, their needs, and goals achieved through their interactions with the artefact. Thus, the problem domain in the vertical dimension in **Figure 13** is divided into two.

The horizontal division of **Figure 13** is concerned with the difference between subjective and objective knowledge, representing the relationship between the designer (the knower) and the design artefact (the known). In philosophical terminology, it represents the interaction between the mind and the world during the acts of producing knowledge and improving an artefact. Mental activities in synthesis refer to objects in the real world, while external activities deal directly with them. In design synthesis, designers also use models/simulations as epistemic instruments to extend their capacity to reason. Thus, the epistemological dimension is a movement between 'analytic' and 'synthetic' design processes, representing the different modes of resolution and composition (McKeon 1966).

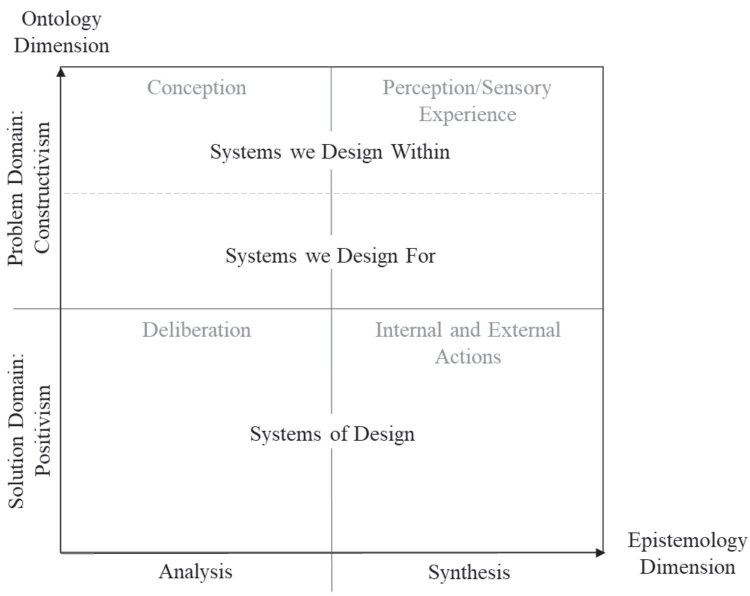


Figure 13. The philosophical framework for ontological categorization of design activities in relation to design epistemology of subjective and objective knowledge.

In the following, the concepts relevant to the different quadrants in **Table 8** are articulated using the ideas addressed in Chapter 3. First, the left quadrant in the problem domain is the conception of ideas based on the perception of experiences, e.g., the formulation of a goal for deliberation. The initial comprehension of a problematic situation is based on past experiences (as suggested by pragmatism, see sub-sections 3.14 and 3.3.3). The constructivist view is useful when information is either unstructured or missing (sub-section 3.3.2). Therefore, in this quadrant, the focus is on the framing and re-framing of problems (and solutions) from different perspectives due to the 'wicked' nature of problems.

The right quadrant in the problem domain can be explained using concepts from pragmatism (see Chapter 3). The problematic situation qualifies the subject to initiate the inquiry intended to transform the current situation. In the context of design, what are the practical consequences (effects and qualities) of the conceived artefact in the given problematic situation? In the pragmatist conceptualization, human activity is situated, determined by the subject and its environment (e.g., physico-spatial surroundings, others, artifacts, and social constructs) (Rylander 2012).

The two quadrants in the solution domain are the contexts in which positivists have developed their design conceptualizations. The left quadrant in the solution domain is focused on problem-solving, which Aristotle (2001) described as deliberation. In the science of the artificial, this process was described as a reduction of the problem to the simplest elements and mechanisms for computer modelling (Clancey 1993; Simon 1977; Simon 1981; Stumpf 2001).

The right quadrant in the solution domain is the simulation, representation, and action context, which proceeds from deliberation and culminates in either representation or construction of the thing. Simon described this process as a merging of the components revealed in analysis into wholes. Simon further proposed the use of symbol systems (conceptual or physical models) to study the consequences of design decisions in terms of function and behavior (Clancey 1993; Simon 1977; Simon 1981; Stumpf 2001).

Lastly, the different types of reasoning studied in part two of sub-section 3.1.3 can be linked to the four different quadrants. In the context of the philosophy of science, three different types of reasoning were defined: deduction, induction, and abduction. Deduction infers a result (the behavior of a structure) from a general rule and a case and is related to the study of (Platonic) forms. Thus, deductive inference is the dominant form of inference in the representation/simulation/action quadrant. Induction, which infers a general rule from sense experiences and a case, belongs to the experience/perception quadrant. Abduction, defined in opposition to deduction, belongs to the deliberation domain. Note that there are other conceptualizations of abductive inference in the context of design. These will be addressed in the following sections.

Table 8. Construction of the philosophical framework for design conceptualizations.

	Analysis	Synthesis
Problem Domain	**Conception** • Indeterminate versus determinate situation • 'Wicked' problems • Interpretation of experiences (properties and structures)	**Perception/Sensory Experience** • Effects and qualities • The situation is composed of the subject and physico-spatial surroundings, other subjects, artifacts, and social constructs • Inductive inferences
Solution Domain	**Deliberation (Problem-Solving)** • Reduction of problems to basic elements • Abductive inferences	**Simulation/Representation/Action** • Motion proceeding from deliberation • Modelling and assembly in symbolic systems (simulations and representations) and material systems to test ideas • Deductive inferences

5.2 Operationalization Based on the Method of Analysis

In this section, the concepts, principles, and elements of ancient and contemporary conceptions of the method of analysis (sub-section 4.3.1) are mapped to the philosophical framework developed in section 5.1. The intent is to operationalize the philosophical framing for the final construction of the new model. As a general comment, the focus of the method of analysis is on causality (see **Table 6** and **Table 7**): the construction of a figure, or the proving of a theorem. Therefore, reasoning and external activities are focused on the application of knowledge. The rest of the discussion progresses according to the logic of solving geometrical problems.

In **Table 9**, the quadrant at the intersection of the analysis and problem domains corresponds to enunciation in the method of analysis, i.e., the conception of the problem. It includes the setting-out of what is given and the definition of the thing sought. The main type of reasoning involved is the transformation/interpretation of the problem but also the decomposition of complex problems into smaller manageable problems.

The quadrant at the intersection of the analysis and the solution domain is divided into two stages, the 'analysis proper' for discovering solution principles and 'resolution' for establishing necessary conditions for object construction. The main types of reasoning include regression (sometimes abduction) and decomposition. In the 'analysis proper', auxiliary constructions are introduced to prove the theorem or solve the problem. The introduction of auxiliary constructions adds information to the problem that connects what is given to what is sought. At the same time, auxiliary constructions also introduce uncertainty, making analysis heuristic and iterative (trial-and-error), as there is no guarantee that the proposed auxiliary constructions will lead to a solution. But when the problems and solutions and the mapping of one to the other are well-defined, analysis becomes logical.

The quadrant at the intersection of the synthesis and the solution domains is also divided into two, mirroring stages/steps in the analysis: 'construction' of the thing sought and the 'proof proper', i.e., construction/assembly of the geometrical figure and proof/demonstration of the reversibility in the 'analysis proper'. The types of reasoning and external activities involved include composition, assembly, and verification in the construction stage and deduction, testing, and verification in the 'proof proper' stage.

The quadrant at the intersection of the synthesis and the problem domain corresponds to the conclusion (*sumperasma*) of the method of analysis, a reversion to the enunciation to confirm what has been demonstrated and proved. The main type of reasoning applied is induction in the general form and in the geometric sense, known as analogy (see the part two of sub-section 3.1.3 for a detailed explanation).

Generally, the function of analysis (heuristic, iterative or logical) is to clarify the problem and to establish the necessary conditions for synthesis. Synthesis reverses the steps followed in the analysis to demonstrate a construction or prove a theorem. However, analysis and synthesis can both lead to something impossible. If at the end of the analysis a construction is impossible, then the synthesis must be impossible too. Synthesis, although determined, can also lead to something impossible, even if the analysis ends in something possible. In summary, the method of analysis sets the stages of problem-solving (the core task of these different stages), the different types of mental and external activities, and general characteristics of the analytical (heuristical, iterative and logical) and synthetical (determined) processes (see **Table 7**).

Table 9. A conceptual design framework based on the method of analysis.

	Analysis	Synthesis
Problem Domain	**Conception: Enunciation of the problem** • Setting-out what is given (*dedomena*) • Definition or specification of the thing sought (*zetoumenon*) • Transformation/interpretation and decomposition	**Perception/Sensory Experience: Conclusion** • Reverterting to the enunciation, confirming what has been demonstrated (*sumperasma*) • Induction and analogy (in the geometric sense)
Solution Domain	**Deliberation (Problem-Solving): Analysis proper** • Proposal of a solution principle • Auxiliary lines (temporal constructions for solving a problem) • Regression (sometimes abduction) and decomposition • Heuristic, iterative or logical	**Representation/ Simulation/ Action: Proof proper** • Proving/demonstrating the reversibility of the analysis proper • Deduction • Testing and verification
	Deliberation (Problem-Solving): Resolution • Establishing necessary conditions for a geometrical figure • Regression (sometimes abduction) and decomposition • Heuristic, iterative or logical	**Representation/ Simulation/ Action: Construction** • Construction/assembly of the geometrical figure • Composition • Assembly and verification

5.3 Operationalization Based on Rhetoric

In this section, the concepts, principles, and elements of rhetoric (see **Table 6** and **Table 7**) are mapped to the framework developed in section 5.1. Similarly to the previous section, the intent is to operationalize the philosophical framing for the final construction of the new model. The discussion proceeds according to the logic used when developing persuasive communication. As in section 5.2, when describing the content of different quadrants, a progression from top-left down, then to the right, and then up to top-right is followed. The description of style/implementation is left to the end.

In **Table 10**, the top-left quadrant is known as invention in rhetoric, roughly corresponding to enunciation in the method of analysis. However, unlike the case in the method of analysis, the problem is not assumed to be given but needs to be invented. The rhetorical analysis starts with the rhetorical situation (*kairos*), and the purpose is to select the intention and topics by analyzing the context, audience, and common ground. The rhetor must adapt to the situation. Although invention also includes the use of deliberation and judgment to find and discover arguments, this stage seems to belong primarily to the epideictic genre of rhetoric, where the focus is on the framing and re-framing of problems and solutions for the celebration of value.

The quadrant at the intersection of the analysis and solution domains, namely, arrangement (*dispositio*) as the deliberative genre of rhetoric, corresponds roughly to the 'analysis proper' and 'resolution' in the method of analysis. This stage involves the organization of topics and parts into a whole and the alignment of appeals with specific parts of the oration.

In the bottom-right quadrant, memory, corresponds roughly to the 'construction' and 'proof proper' stages in the method of analysis. Memory as a stage is specific to oral speech. In ancient times, mnemonic devices were often used to memorize and recall the elements of speech.

The top-right quadrant, delivery, mirrors the invention stage. This stage has two faces, the delivery of the speech and the judgment by the audience. Delivery is a mediation of the qualities and effects of actions, accomplishments, and things. Judgment, followed by delivery, is concerned with the testing of ideas, the proving of conclusions, and the validation of statements established in the invention stage. This stage seems to belong primarily to the judicial genre of rhetoric.

The style/implementation stage is considered here separately, as it has a specific place in rhetoric. In the method of analysis, implementation is not considered problematic. When demonstrating a theorem or solving a problem, complex entities are reduced to their most basic elements (e.g., points or lines) and assembled into wholes using well-known geometric techniques (e.g., using a compass and an ungraded straightedge). However, implementation is crucial in the context of rhetoric, e.g., as part of the process of creating a persuasive speech, where, for example, choosing a proper pitch when delivering ideas affects the quality of the speech.

The art of rhetoric is mainly concerned with persuasion of an audience. This requires analysis of a given situation, common ground, framing and re-framing of problems and solutions, continuous judgment, and intention and motivation arrived at through the process of finding and discovering arguments. In other words, rhetorical discourse concerns the production and delivery of a persuasive speech. In summary, rhetoric involves three genres of argumentation; the stages in the delivery of a persuasive speech; core tasks entailed by these different stages; and modes of persuasion (see **Table 7**).

Table 10. A conceptual design framework based on the rhetoric.

	Analysis	Synthesis
Problem Domain	**Conception: Invention (*inventio*)** • The epideictic genre of rhetoric • Given situation (*kairos*): place and time to consider opportunities for words to be useful and appropriate • Common ground (*endoxa*) of shared values, facts, and presumptions • Framing (re-framing) of judgments • Intention and motives (a term encompassing the commitments, goals, desires, and purpose that lead to action) • Finding and discovery of arguments (topoi)	**Perception/Sensory Experience: Delivery (*actio*)/Judgment** • The judicial genre of rhetoric • Delivery using different means of expression • Qualities and effects of actions, accomplishments, and things • Judgment of the speech by the audience (the art of testing arguments, proving conclusions, and verifying statements)
Solution Domain	**Deliberation (Problem-Solving): Arrangement (*dispositio*)** • The deliberative genre of rhetoric • Organizing the topics into a speech, parts into a whole; • Alignment of appeals (character, logic, and emotion) with specific parts of the oration	**Repesentation/ Simulation/Action: Memory (*memoria*)** • The deliberative genre of rhetoric • Memorization of a speech, using, for example, mnemonic devices
	Style (*elocutio*)/Implementation • The deliberative genre of rhetoric • An artful expression of ideas using different rhetorical methods and devices	

5.4 Construction of a New Design Model

A new prescriptive design model based on the philosophical concepts and two strategies of inquiry investigated now follows. Specifically, it is investigated whether the method of analysis and rhetoric can be integrated into a common framework, that is, including the contents of **Table 9** and **Table 10** in the new design model. Design is a complex phenomenon consisting of situated subject- and object-oriented internal and external activities. Due to this complexity, a model is envisioned as a means to express the descriptive and prescriptive relationships between different factors (as described in sub-section 4.1.3 and section 4.4) of the design process. The new model is expected to support the development of a better understanding of the design process as a whole. Its construction makes use of the ideas developed in the previous three sections and mapping of contemporary concepts and terminology to the features of the method of analysis and rhetoric investigated in Chapter 4 and Appendix II. The new model is built up in a gradual progression from the general to the specific.

5.4.1 Design Stages

In the method of analysis, there are six stages to the solving of geometric problems (see **Table 8**), and in rhetoric, five stages to the delivery of a persuasive speech (see **Table 10**). Before an alignment is proposed, the overall organization of stages is presented. The vertical division of the sections in **Figure 14** reflects the environment-artifact system division (see **Figure 13**). The horizontal division of the sections represents the division between design and making (including conceptual and material models and artefacts) (see **Figure 12**).

The alignment of stages in the method of analysis and rhetoric can be accomplished in different ways. First, human activity can be interpreted as a multi-scale phenomenon. The systemic-structural theory of activity classifies human activity according to four different levels, activity, task, action, and operation (Bedny and Meister 2014). On the basis of this conceptualization, it may seem that there are unique process structures on each of these four levels. Alternatively, the design process can be conceptualized under the assumption that the staging of human activity can be viewed on a meta-level, i.e., the basic structure is the same across different levels. Here, the second approach is followed, meaning that processes are considered self-similar across different scales of process description (generally, macro, meso, and micro): they are fractal in nature (Gleick 2011).

In the method of analysis, the stages include the conception of the problem (*enunciation*), the analysis proper, and resolution in the analysis part and construction, the proof proper, and the conclusion in the synthesis part. Synthesis has a dual meaning: in the design context, it involves the development of design representations and models for the testing of ideas and drawing of conclusions; in the actual construction of a building, the synthetic stage corresponds to making, assembly, testing, and delivery/operation. In rhetoric, the stages include invention (problem and solution framing), arrangement, style, memory, and delivery. In his interpretation of the stages of rhetoric, Buchanan (2001) proposed five arts of design thinking (see Appendix II). According to Buchanan (2001), these stages do not occur in sequence but somewhat simultaneously – they more or less overlap. An alignment between the different stages is proposed as follows.

Invention corresponds approximately to problem clarification in the method of analysis. The main difference is that in rhetoric the problem is not assumed to be given. Design from the perspective of design rhetoric commences with awareness of a problematic situation (as in design pragmatism (Dalsgaard 2014)), the recognition of a gap – the discrepancy between how things are and how they ought to be – and the establishment of overall purposes and goals. In design rhetoric, invention also involves the development of ideas and requirements, the transformation of purposes into use functions and properties and product specifications. These steps are known as problem and solution framing (see **Figure 14**).

Arrangement and disposition correspond broadly to the analysis proper and resolution in the method of analysis. In design rhetoric, these refer to the arrangement of ideas, requirements, and issues. Kroll and Koskela (2014) proposed an innovative two-step abduction to conceptualize these stages: the designer infers the working principle for the desired requirement first and then the form, configuration, and structure of the artefact that utilizes the working principle. These two steps correspond to conceptual design and design embodiment, respectively. Arrangement ends with the establishment of the necessary conditions for solvability/constructability of the proposition. In this work, these stages are collectively referred to as the generation of the solution.

Style, which also includes the memory stage, corresponds in part to the construction of the geometric figure in the method of analysis. In the method of analysis, style is not considered to be essential, whereas in the delivery of a speech it plays an important role. For example, in the V-model (see Appendix II), it is often assumed that designers will use off-the-shelf products, obviating the need for a detailed design (Forsberg et al. 2005). In contemporary production conceptualizations, this is known as the communication or transmission of information through the making of parts (Fujimoto and Miller 2007). This is a movement from the establishment of a detailed design at the end of the analysis to the making in the synthesis and to the beginning of assembly. These stages are collectively referred to as implementation.

Evaluation of the objective and qualitative worth of products has two meanings. In the design process, the designed configurations need to be tested and evaluated against functional (performative) requirements. In the method of analysis, this corresponds roughly to construction (composition/assembly of the individual objects into partial and final wholes) and the testing of constructions and theorems. The latter is the deduction of behavior during the testing of the designed artefact against the functional requirements established in the analysis. These stages (construction and testing) are collectively referred to as development.

Evaluation by the audience also arises during delivery, which corresponds roughly to the conclusion in the method of analysis. It is the delivery of the designed artefact, the outputs of the design process during design, and the actual artefact after its making. The delivery during design corresponds to the communication of designs to customers and users and justification of the decisions made (Goldhagen 2017), including consideration of the artefact's effects on the environment and expected qualities of it. In the case of the actual construction of a building, this would correspond to the handover, including the training of users, delivery for use, and maintenance instructions (Teicholz 2013). As stated above, this quadrant also involves evaluation of the artefact by a particular audience and the delivery of value as the expected outcome of project delivery (Zwikael and Smyrk 2011). This, from the rhetorical perspective, invites a response from customers and users, who perceive the designs from their own perspective of expected purposes and uses (Vermaas and Dorst 2007). Evaluation is determination of whether customers and users are satisfied with a designed artefact or not. The two stages (delivery and evaluation) are collectively referred to as transition.

As an outcome, the artefact's environment-related stages are named according to design rhetoric. The artefact-related stages are named according to the two pillars of design conceptualization. The latter is justified because design and the making of a speech are comparable to the stages of constructing a figure in the method of analysis. The alignment of the different stages, summarized in **Figure 14**, is not too different from that in existing models. For example, the analysis-design-development-testing cycle in agile software engineering resembles the one here (Demir and Theis 2016; Sutherland 2014), the difference being in the details. The model here is a strategic sequence of stages for the design process, aligning the two different perspectives of interpretation and causality.

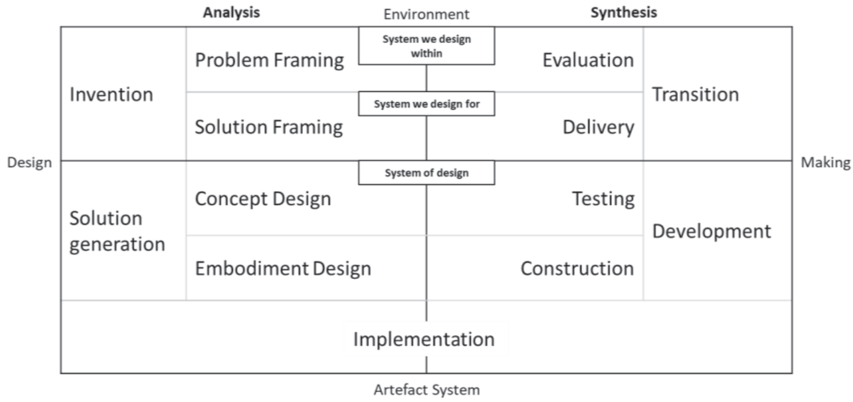


Figure 14. Alignment of the stages in the method of analysis and rhetoric.

5.4.2 Design Iterations

Design is a process of conceiving something that does not exist yet, requiring creativity and imagination from the designer on how things could be. In the design process, designers are facing uncertainty, instability, uniqueness, and conflicts as an opportunity for knowledge creation (Schön 1984). Therefore, iterations, either intentional or unintentional, are part of the design process. According to Wynn and Eckert (2017), the three classes of iterative stereotypes include the progressive (productive iteration for generating information and knowledge), corrective (for testing and responding to unintended consequences), and coordinative (managerial) iterations. Although progressive and corrective iterations are directly related to the design process, these are also influenced by the managerial iterations, which have a strong bearing on the design work.

In the method of analysis, analytical inquiry can be either logical or heuristic or iterative (see **Table 9**). When the problem (function) and the conceptual 'machinery' for transforming the design problem into solutions is analytically described, the process becomes logical. Namely, the application of scientific knowledge and methods has been the underlying tenet of engineering practices. Thus, engineering design has leaned towards logical inquiry. When a problem is vague or there is no pre-established knowledge or structured method for solving a problem, analysis becomes heuristic. In this case, analysis may lead to something impossible, as no necessary conditions exist or could be defined for solving the problem. Therefore, iterations are required. They are referred to here as progressive iteration.

Synthesis in the method of analysis is determined (see **Table 9**). The steps in the synthesis are the reverse of the steps in the analysis, and the results are verified against the decisions made in the analysis. When the results in the synthesis deviate from the conditions established in the analysis, either the solution is impossible or corrective iterations need to be carried out. The latter means that either the problem or the solution idea must be changed. However, synthesis also has a progressive function. In particular, when a problem overwhelms the mind, the designer offloads parts of the problem from memory into the world (Tversky 2011; Tversky 2015), by using (conceptual or material) models (subsection 3.1.2).

In rhetoric, design problems and solutions are mutually dependent. In addition to the indeterminacy of the design process, rhetoric addresses designing with and for humans. In the design process, interpretation for the framing and re-framing of problems and solutions from different perspectives is needed, and the design results are validated against expected effects and qualities as the practical consequences of delivering the designs. This means that the problem, solution, and audience spaces are co-developed (Halstrøm and Galle 2015). For example, in the V-model, the iterations at any stage in the design process are expected to extend all the way up to the users and user needs and down to the lowest level configuration items (Forsberg et al. 2005). Thus, rhetoric also addresses managerial iterations.

In summary, the three types of iterations involved are the progressive and corrective in the method of analysis and the managerial in rhetoric. On the basis of the four quadrants depicted in **Figure 13**, iterations within and between the different classes of situated mental and external activities are presented in **Figure 15**.

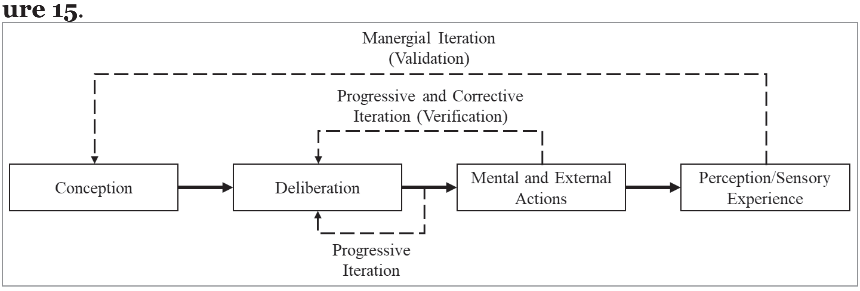


Figure 15. Three types of iterations within and between the different classes of mental and external actions.

5.4.3 Causal Structure of Design

In the context of design, models and modelling have been used to represent and simulate products and processes, or both. For example, Gero (1990) argued that designers use prototypes as epistemic means to understand what could be. The essential characteristic of models is that they reduce reality by assuming the underlying structure (form) of the phenomena to be described. As the interest here is in the understanding of the design process, as in Kannengiesser (2009), the causal process structure represents the relationships between process elements: input, transformation, and output. Inputs are transformed into outputs through the situated mental and external design activities. For example, the input could be the given problematic situation, goal(s), or the requirement(s). The output is the result of transformation, for example, the solution principle from the transformation of requirements.

Vermaas (2013) suggested a causal chain after comparing different design ontologies and definitions of the term function (see Appendix 2). He argued that design proceeds from goal, action, function, and behavior to structure. However, Vermaas (2013) did not explicitly consider the problematic situation, when the goal is not provided at the outset, and the implementation of designs and how design proceeds in the synthesis.

Other sources providing inspiration for a definition of the causal structure of designing are the concepts related to design reasoning. Deductive, inductive, and abductive reasoning can be represented in a syllogistic form (sub-section 3.1.3): premise + rule = conclusion. For example, Dorst (2011) and Kroll and Koskela (2014) used the syllogistic form, replacing 'premise' with 'what', 'rule' with 'how', and 'conclusion' with 'result' or 'why'. As Kroll and Koskela (2014) interpreted it, 'what' corresponds to the 'artefact' (embodiment), 'how' to the 'mode of action' and 'way of use', and 'result' either to the 'function' or 'value'. The specific type of inference applied depends on what is given or not given (see Chapters 3 and 4).

However, as the conceptualization of design of Kroll and Koskela (2014) is based on the technical view of design, they have neglected aspects related to the environment. The 'value' and 'way of use' are considerations related to the product's environment and determined before the solution design. That is, the value to be captured by the product and the way it will be achieved through user actions are considered before defining the function, mode of action and embodiment. This is central to rhetorical design: design starts with the problematic situation, passes through implementation in the medium, and moves back to delivery and then judgment by the audience (see sub-section 5.4.1. for the description of stages).

On the basis of these concepts, **Figure 16** depicts the causal structure proposed. In addition to the elements proposed by Vermaas (2013), the model includes elements related specifically to rhetoric: the problematic situation (gap and satisfaction) and the actual implementation of the artefact in details and components. Additionally, the steps related to the synthesis (the inquiry forward), which mirror the steps in the analysis (the inquiry backward), have been elaborated on (sub-section 4.3.3).

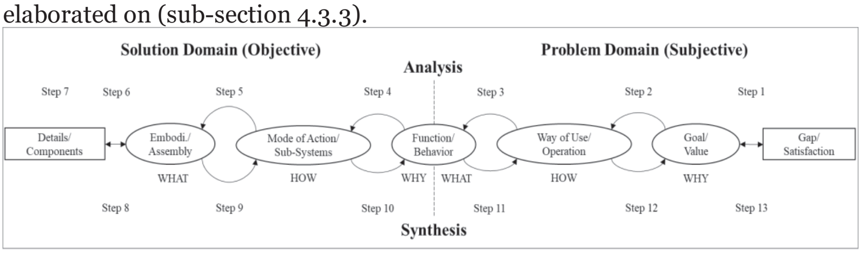


Figure 16. Causal chain of design from gap to details in analysis and from components to satisfaction in synthesis.

5.4.4 Mental and External Activities

As design activity is about how designers think and behave, it is important to elaborate on the types of situated mental and external actions transforming inputs to outputs in the analysis and synthesis. The discussion proceeds through the stages established in sub-section 5.4.1, and the types of mental and external activities in the method of analysis and rhetoric (see **Table 9** and **Table 10**) are aligned to the causal structure defined in sub-section 5.4.3. However, while the types of situated mental and external actions have been mapped to the different steps in **Figure 16**, this does not mean that they are the only ones that are operational. The intent is rather to indicate where specific types of mental and external actions are dominant.

Due to the limited information available to the designer, the problem and solution framing at the intersection of the analysis and problem domains is the challenging. In Chapter 4, it was argued that problem clarification involves the transformation/interpretation and decomposition of a problem. However, rational types of reasoning may have limited value. Instead, according to Koskela et al. (2018), the types of reasoning involved may be strategic abduction, abductive transformation, abductive decomposition, and abductive invention of requirements (see Appendix II).

There is yet another type of reasoning, namely, intuitive reasoning (Claxton 2000; Dreyfus et al. 2000). Dreyfus et al. (2000) proposed that intuition is related to the development of an understanding of a situation as a whole without a specific rationale. He defined six key aspects: pattern recognition, similarity recognition, commonsense understanding, skilled know-how, sense of salience, and deliberative rationality.

Taura and Nagai (2017) distinguished between 'experiential intuition', "that which enables instantaneous decision-making following patterns recognized based on one's experience", and 'associative intuition', the "feeling how something is or how something is related to another, based on one's sensibility". They argued that experiential intuition operates in problem-oriented design accompanying the elimination of fixation, i.e., in analytic inquiry, and associative intuition in solution-oriented design accompanying a flash of insight, i.e., in synthetic inquiry. However, as intuition is generally still an understudied phenomenon, it has been omitted from the final model.

Solution generation at the intersection of analysis and the solution domain (objective) starts when the environment has been frozen: the problem has been objectively defined and the framing of a solution has been proposed. In this domain, the types of reasoning in the method of analysis and rhetoric overlap. The main types of reasoning include regression (sometimes abduction) and decomposition, which are concerned, respectively, with cause-effect and part-whole relationships (see sub-section 4.3.1).

Implementation corresponds to communication (detailed design) and the making of parts. In the context of productive sciences, this means the transmission of information, from the designer, mediated, for example, using different types of visualizations and/or gestures, to the physical medium. In the fundamental arts of design thinking (Buchanan, (2001), this corresponds to the fifth art, which is concerned with expression and style, thus connecting analysis and synthesis.

Development at the intersection of the synthesis and solution domains (objective) begins when deliberation is finished and parts have been made. Synthesis involves intra-mental, extra-mental and external actions and operations. As in the previous domain, the types of mental and external actions in the method of analysis and rhetoric overlap. The main types of reasoning are composition and deduction, while the main types of external activities are assembly, testing, and verification.

Delivery and evaluation at the intersection of the synthesis and problem domains (subjective) are dominated by rhetoric, while dedicated to delivery, justification, evaluation (inductive reasoning), and validation. However, the types of reasoning involved include the induction and inductive analogy, also known as analogical reasoning (see the part two of section 3.1.3). **Table 11** summarizes the dominant types of mental and external actions and operations related to the stages in **Figure 14** and the steps in **Figure 16**.

Table 11. The dominant types of mental and external actions and operations associated with the different steps in **Figure 16**.

	Step	Analysis	Step	Synthesis
Problem Domain	1	Transformation (interpretation) and decomposition	13	Induction (evaluation) and analogy; delivery, justification, and validation
	2		12	
	3		11	
Solution Domain	4	Regression (abduction) and decomposition	10	Composition and deduction; assembly, testing, and verification
	5		9	
	6		8	
	7	Communication	7	Making

5.4.5 Construction of the New Design Model

In this sub-section, the new design model is assembled based on the concepts and elements discussed above. In the conception quadrant in **Figure 17**, the problem and solution framing stages include the steps connecting gap to goal (purpose) and goal to the way of use and function. The two different types of mental actions, including transformation (interpretation) and decomposition, mediate the different design states.

In the deliberation quadrant, steps connecting requirements to the design concept (mode of action), design embodiments, and design details are mediated by two different types of mental actions, regression (sometimes abduction) and decomposition. Analysis in the second quadrant can be heuristic, leading to progressive iterations, depending on whether the problem or solution is novel or not. In routine design tasks, analysis becomes logical; the mapping between the problem and solution domains, from function to structure, is generally well-established. Therefore, the designer is primarily concerned with demonstrating and proving that functional requirements have been met.

Implementation, the movement from design details to components, has a bridging function. This has two meanings, depending on the context. In a design context, it is concerned with the translation of designer's ideas into representations. In the construction context, it is concerned with the making (e.g., fabrication and transportation) of components.

The mental, symbolic and external quadrant encompasses the movement from components to assemblies, from assemblies to sub-systems, and from sub-systems to behavior. The main mental activities are composition and deduction, while the main external activities are assembly and testing. These steps are the reverse of the steps in the analysis (see **Figure 16**). The formal procedure for assuring the compliance of the analytic and synthetic processes with the design and making processes is known as verification.

Steps in the perception/sensory experiences quadrant, related to delivery and evaluation, encompass the movement from behavior to outputs and effects, from outputs and effects to outcomes and qualities (values), and from outcomes and qualities to satisfaction or gap. The main types of mental and external activities include induction (evaluation), analogical reasoning, delivery, and justification. At every step, the validation process assures compliance with customer/client and user goals and needs by making it possible to learn from the observed impact of design decisions on the environment.

These steps and the interdependencies between different states are depicted in **Figure 17**. Thus, the new design model presents the following process structure: stages, design iterations (in the analysis and between the analysis and synthesis), causal structure (sequence of transformations), and types of mental and external activities transforming design from one state to another. However, it is noted here that the new design model is a necessary simplification of the actual process. First, design is not a linear process, and the design process does not always follow an established sequence. Also, while specific types of mental and external actions and operations are dominant in the different stages and steps, the types involved, in practice, may also include ones not addressed in this research (e.g., classification).

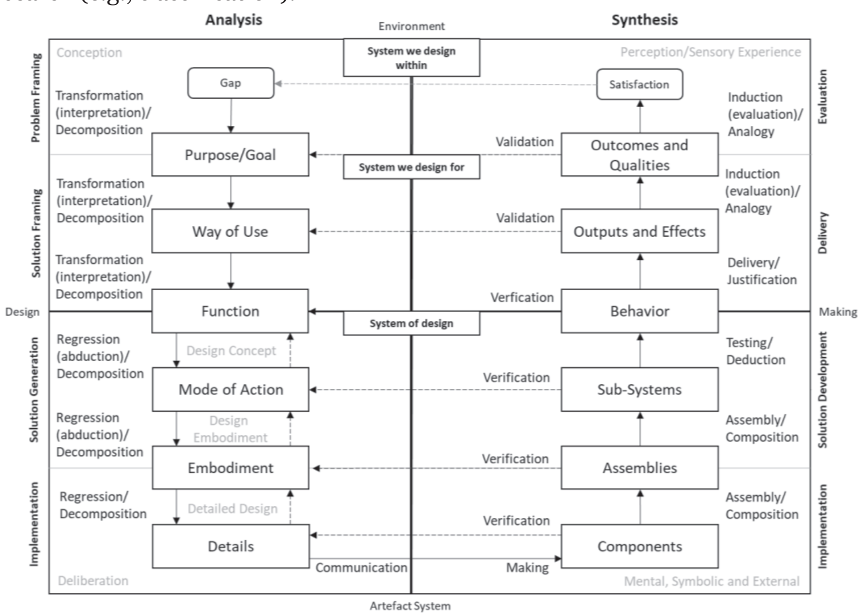


Figure 17. The new design process model.

5.5 Chapter Summary

In this chapter, the intent was to provide an answer to the question of what kind of new design model can be synthesized based on the method of analysis and rhetoric.

In the first part, the philosophical aspects of design theory were addressed, including the underlying assumptions, ontology, epistemology and categorization of domains and design contexts. Designing was defined broadly as human activity and more narrowly as internal non-routine activity. A pragmatist framing was proposed to enable the synthesis of the two fundamental design considerations, causality and interpretation.

In regard to ontology, six different categories of activities were defined, sensory experience, perception, conception, deliberation, mental or symbolic representations, simulations, and external action. In regard to epistemology, designing was defined as a movement between different categories of activities mediated by different input and output states (divided into three categories: mental models, conceptual models, and material systems) with the aim of creating, applying, and justifying (verifying and validating) knowledge.

Sensory experience, perception, and conception were categorized as subject-oriented activities belonging to the problem domain; while deliberation, mental or symbolic representations and simulations, and external action were categorized as object-oriented activities belonging to the solution domain. The problem domain was sub-divided into two contexts of designing, the system we design within and the system we design for. The solution domain was categorized as the system of design. Finally, for each category of fundamental activities, a set of key characteristics were defined.

To operationalize the different categories of activities, the philosophical concepts were aligned with the concepts and principles of the method of analysis and rhetoric. Notably, philosophical concepts were aligned with the stages of problem-solving, the core task of these different stages, the different types of mental and external activities, and the general characteristics of the analytical processes (heuristic, iterative and logical) and synthetic processes (determined) of the method of analysis. Philosophical concepts were also aligned with the three genres of argumentation, the stages for delivering a persuasive speech, the core tasks of these different stages, and the appeals of persuasion.

A step-wise process was followed to construct a new design model. The intent was to synthesize a new design model based on the two strategies of inquiry. The two complementary strategies of inquiry provided both the descriptive and prescriptive ideas needed to conceptualize design activity. These strategies of inquiry helped to define the sequence of stages, design iterations, the causal structure of designing, and types of mental and external actions.

Regarding the stages of designing, the artefact's environment-related stages were named according to design rhetoric, while the artefact-related stages were named according to the two pillars of design conceptualization. The resulting model represented the strategic sequence of stages: a movement from the rhetorical perspective to the method of analysis and back to the rhetorical perspective. Due to the inherent uncertainty of design, three different types of iterations were defined, the progressive and corrective in the method of analysis and the managerial in rhetoric. A causal structure consisting of the different types of transformations (changes) required to deliver the design were defined, altogether representing 13 steps. Unlike in many other design theories and models, the steps related to the artefact's environment and synthesis were included as well. The causal structure was then the basis for defining the different modes and types of mental and external activities dominant in the specific stages of designing. The final step in the construction resulted in a new model, as illustrated in Figure 17.

That all our knowledge begins with experience there can be no doubt.

Immanuel Kant

6. Evaluation of Practical Utility of the New Model through Case Studies

The objective here is to evaluate the utility of the new design model proposed in the previous chapter through three case studies. The emphasis in the first and second case studies is on the methodological questions of design; in the third case study, on the development of model instantiations. In all three cases, an application of the descriptive as well as prescriptive outputs of previous chapters to a specific context and instantiations for improving practices are required.

This chapter is divided into five sections: section 6.1 addresses the early stage of design in the development of an innovative warehouse concept; section 6.2 addresses a case study on the designing of robust energy and cost efficient buildings; section 6.3 presents a case study involving the design, implementation, and evaluation of prescriptions for improving design and management practices in a design company; section 6.4 summarizes the findings across the three different case studies; and finally, the chapter concludes with a general summary in section 6.5.

6.1 Case Study I: The Early Stage of Design of a New Concept for Warehousing

This case study aims to demonstrate the usefulness of the new model and its potential to prescribe design activity and its management in the early stage of a design project. The main focus was on the development of a new concept for warehousing by establishing goals, needs, ways of use and functions of a new building to facilitate the personal and business operations of users.

6.1.1 Case Study Method

The first version of the case study was published by Pikas et al. (2016) and involves research carried out in the second half of 2015. As participative action research, the study focuses on the early stages of design and designing. The author of this thesis participated in the development of a new warehouse concept for small and medium-sized businesses involved in wholesale, sales, services, or a combination of these. The objective here is to evaluate the usefulness of the new model, i.e., how well the common framework supports design and design management practices. The focus is mainly on the social and interpretative dimensions of designing. Overall, the research was divided into four stages: (1) the given situation and start-up of the project, (2) situation analysis and goal formulation, (3) study of user needs, and (4) solution framing.

As part of the first stage, a design project team was formed, consisting of representatives from the design office and the client's organization. Practitioners of some design disciplines were only involved in the later stages, such as the structural and building service engineers. In the second stage, ten similar existing facilities in and around Tallinn, Estonia, were studied, resulting in a report which summarized problems, existing solutions, primary users, use activities, and user needs/requirements. In the third stage, the report became the basis for the formulation of the use plan and expected characteristics of the facility. In the last stage, a product concept was developed iteratively over several weeks. In these stages, observations, document analysis, and group work research methods were employed.

6.1.2 Given Situation and Project Start-Up

One of the largest Estonian companies in the field of logistics parks and warehousing services was looking for new opportunities to expand their business services. Until that moment, they had focused on large-scale logistics parks but were planning to start providing warehousing services to small and medium-sized companies. The company was interested in developing a generic warehouse concept that could be tailored to a specific type of parcel. This was the problematic situation, or gap, according to the new model (see **Figure 14**), posed by the owner.

At the beginning of a project, a small team was formed, consisting of client representatives, the architect, the design project manager, and the author of this thesis. Structural and building services engineers were later included in the solution framing stage. A contractor was also engaged to provide feedback on constructability and the target cost of the proposed design concept during the evaluation of the solution framing.

The design process was divided broadly into three phases: (1) situation analysis and goal formulation; (2) establishment of the ways of use and product characteristics; and (3) solution framing. These correspond to steps 1, 2, and 3 in **Figure 16**.

Situation Analysis and Goal Formulation

In step 1 in **Figure 16**, similar existing facilities were located in and around Tallinn, Estonia, and the project team selected ten of them for closer study. The team paid a visit to these ten facilities over the course of two and a half days. The result is a 20-page report summarizing problems, existing solutions, primary users, use activities, and user needs/requirements. The following observations were made:

Complex nature of the client: This is probably the case for many building owners (Bertelsen and Emmitt 2005). All the companies investigated were importing goods, and depending on the type of product, they were involved in either wholesale or retail or provided product-related services (e.g., tire services), and this determined the kind of functional spaces needed. The following target client categories were identified: wholesale, product-related services, or a combination of these.

Typical spatial layout:

- Average floor space per company was 317 m^2, covering storage, office, showrooms, or a combination of these. However, the distribution across companies varied remarkably, and with the omission of one small company from the sample, the average floor space rose to 568 m^2.
- There was no correlation between the number of people working at the company and the size of the storage and showroom areas.
- The average office floor space per person was 14 m^2. However, most of the tenants indicated that the figure was too high and more storage space was required. It was concluded that about 10 m^2 of office floor space per person would be optimal.
- Showrooms should be optional and if required, located on the first floor, meaning that companies who require a showroom can use the space as a showroom and others as an office space or service space.

Limitations of building form, layout, and solutions:

- Offices spaces were designed throughout the entire depth of the building on different floors. A problem arose in the case of companies who had storage spaces on both sides of their office spaces and thus had difficulty moving goods from one side to the other. They had to transport goods through office space or from the outside. The latter posed problems in winter.
- Several solutions had storage space rising through three floors, resulting in heights of about 9-10 m. For workers responsible for handling goods this was a poor solution, as it complicated the process of storing goods.
- Office spaces were poorly laid out, as people working there indicated that they did not have space for resting, eating, or holding meetings.
- Thresholds between showrooms and storage spaces hindered the transporting of goods.
- Overly long shelves hindered passage through the transportation doors.
- Several companies indicated that the transportation doors for transporting goods in and out of storage space were either too high or wide.
- Lights and ventilation ducts were crisscrossed by roof trusses.

Technical solutions:

- The buildings investigated were made of precast concrete or steel structures, including sandwich panels and steel or concrete structural frames.
- Heating and cooling systems, e.g., air to air heat pumps, were mostly electric.
- Five out of ten buildings had skylights in either the office or storage sections, as the storage buildings could be relatively deep.

The principal goal of the design project was defined as follows: "Modular, flexible, spatially optimal, cost and energy efficient combined production, service, storage and office building for small and medium-sized wholesale, retail or service companies."

Establishing the Way of Use and Product Characteristics
In step 2 in **Figure 16**, the report developed in the first stage and the established goal became the basis for the conceptualizing of the ways of use and product characteristics. The overall preferred way of use (concept of building operations) for business activities was that goods would be transported from the back of the building, and clients would enter from the front. Functional decomposition depended on the business type and company's main activities. The types of businesses and the company's main activities became the basis for spatial decomposition – which reflects how the future users would want to use the building:

- **Office spaces**: must be aesthetically appealing, comfortable, functional, and well-lighted. Companies want to provide good working conditions for workers. The office spaces must be well laid out, providing enough workspaces, a kitchenette, and a toilet. Typically, companies with a total floor space of about 400 – 600 m^2 also need a small meeting room.
- **Showrooms**: Not all companies require this type of space; those who do have varying size requirements. Thus, floor space on the first floor should be multi-functional, ready to be used as a showroom, reception space for clients, or as office space.
- **Service areas**: Companies that require service spaces must have administrative rooms that are at least two floors high. Some companies that provide services also provide shower rooms and dressing room for workers.
- **Storage spaces:** In general, goods can be divided into two groups according to size: small and large. Larger goods are moved with forklifts and smaller ones by hand. Companies need enough space between shelves to manoeuver with forklifts. Regarding indoor climate, few companies had products that required controlled indoor temperature and humidity levels.

Based on the established ways of use, user-specific product characteristics were determined. Instead of compiling overly extensive documentation, the team produced a two-page design concept paper, the result of several iterations, as the basis for the schematic design. **Table 12** describes the value structure based on the ways of use.

Table 12. Summary of aspect categories and expected performance.

Nr	Aspect	Expected Performance
		Suitability
1	Modular spaces	Space range per module: 200-600 m^2
2	Flexible storage and showroom spaces for expansion	Movable internal walls and flexible building services
3	Effective form, spatial layout, and storing of goods	• Office spaces will be along the front exterior wall of the building • Storage spaces will have optimal paths for the movement of equipment and transportation of goods • Office spaces must have a small kitchenette and toilet on both the first and second floors • The width of the corridor will be set according to the maneuvering radius of forklifts with a lifting capacity of ≤ 1.5 tons. Expected width between shelves ≥ 3.2 m • To maximize storage space, the optimal spacing of shelves will have two or three corridors • Enough office space to ensure about 10 m^2 per person • Size of transportation doors: height ≥ 2.8 m and width ≥3 m • The clean height of storage space under trusses: 6m (clean height for stowing is 4.5 m)
		Aesthetics
5	Comfortable working conditions	Well-lighted working spaces and aesthetically appealing materials
		Sustainability
6	Energy and cost efficiency	Cost effective and energy efficient solution: minimum requirement is B-class (consider renewable energy)
7	Indoor climate control	Users can control indoor climate, heating, cooling, ventilation, and lighting
		Durability
8	Optimized structures and details	Cost-optimized solutions for structures and details
9	Optimal maintenance costs	High durability materials with a long lifespan (50 years for structures)
		Construction Cost
10	Construction cost	≤ 400 €/m^2 (target cost)

Solution Framing

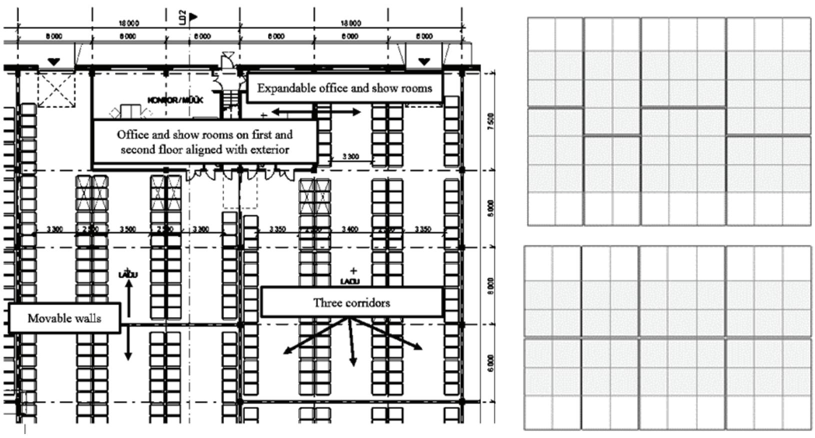
In step 3 in **Figure 16**, product concept development took place over many weeks in an iterative manner. The architect prepared a first draft based on the selected concept, linking functional requirements to physical characteristics. The starting point for the architect was the storage space with two or three corridors between shelves and with the size of the columns initially 300x300mm. A model was prepared using Graphisoft ArchiCAD to facilitate communication between the architect and the client.

The overall concept was a modular warehouse which would meet different user needs. Modules on the building level were defined as rectangles of varying sizes and were arranged in different ways to form a whole building. The maximum size of the building depended on the specific site, zoning requirements, and design requirements set by the local government. The driving concept for the architect was “organized chaos”.

The main modules of the building were divided into 6x6 m sub-modules, mainly due to limits imposed by the structural spans. However, the first module, intended for office spaces and showrooms, was 7.5 m deep. The architect also had to consider other constraints, such as transportation door width (≥3 m) and height (≥2.8 m), which was the basis for selecting the dimensions of first-floor windows. During the iterative process, several layouts were proposed, and during each iteration, the architect focused on one specific aspect (e.g., layout of the building, or building façade).

After a few iterations, structural engineers, HVAC engineers, and electrical engineers were brought in to perform the calculations necessary to verify the architect's assumptions and to propose conceptual solutions for different systems. As a result, column dimensions were changed to 400x400mm due to fire safety considerations.

The greatest challenge was to find appropriate solutions for the flexible spaces, which would be considered a significant innovation. As shown in **Figure 18**, the end walls of each section are movable. It is the same case in the offices and showrooms. However, these can be expanded only to the right and left relative to the front and back of the building. Flexibility was also required in the building of the lighting systems and services since they would have to accommodate changes in the layout of the building. Therefore, the meters for measuring energy consumption would be placed at the front of every rentable section of the facility. Lighting systems were connected through outlets; in the case of movable walls, the connections could be moved as well from one outlet to another. The floors on the second floor would be built from standardized prefabricated wooden frame panels, and the interior walls from sandwich panels that can be easily assembled or disassembled.



a) b)

Figure 18. Building with combined storage, office, and service and showrooms: a) flexibility of spaces made possible with the use of movable walls; and b) two examples of modules and composition.

At the end of the solution framing stage, an Estonian contractor was brought in to evaluate constructability and make an early cost estimation. The model was used to determine quantity take-off and make constructability assessments. The target cost was set at 400 €/m²; the contractor estimated 413 €/m². However, the team also anticipated that the calculated cost could be reduced by developing a more detailed design and better technical solutions.

The client also used the concept produced to validate the business model on the market. They used layouts and BIM based renderings to create a fictitious advertisement. Altogether, the project was viewed about 20 times on the website, and three persons called and asked for more details. Although interest might be considered low, it was also understood that organizations looking for new spaces are primarily interested in facilities which already exist. In the end, the client accepted the proposed product concept.

6.1.3 Discussion and Summary

Overall, the case study indicated the importance of a common design process as a way to ensure effective communication. In the case study, the steps of the different stages, specifically the activities and corresponding outputs, were described. They were as follows: (1) given situation and project start-up, (2) situation analysis and goal formulation, i.e., observation of existing solutions and needs of users to define the overall goal; (3) establishment of the way of use and product characteristics for the design conceptualization; and (4) solution framing focused on the realization of the product concept. The first stage is primarily a managerial activity corresponding with design system design. The following stages are design stages.

The case study began with the problematic situation defined by the client: to develop a generic warehouse concept. This marked the beginning of project delivery, with the focus on the setting up of the project, including the establishment of the design team and the overall process for delivering services. On the macro level, the process followed the steps 1 to 3 outlined in **Figure 16**, from the establishment of overall project goals to the determination of the ways of use and the framing of the solution concept.

In the early stages of design, design activity was primarily concerned with interpreting what potential future users wanted and needed and what ought to be. However, this did not mean that the causal aspects did not have to be considered. They were especially evident during the framing of the solution concept. For example, the type and size of forklift, which depended on the types and weights of goods to be moved, would determine the width required between the shelves. Another case in point involved the dimensions of columns, which were changed after the initial structural calculations from 350x350 mm to 400x400 mm.

The first stage was concerned with problem formulation. The aim was to develop arguments for customers and users and discover new things through these arguments. The next two stages were primarily concerned with solution framing. In the building design domain, this is often described as the user study and building programming (Fischer et al. 2017). This is in agreement with the alignment of stages of the method of analysis with those of rhetoric in sub-section 5.4.1.

However, several iterations of the solution framing demonstrated the nature of the process structure at the collective and individual levels. For example, the architect developed several ideas during the product concept development stage that were evaluated collectively. Similarly, the development of possible technical solutions and ideas for modularity and flexibility were achieved through discussions between the architect, engineer, and client.

In this process, the designs were communicated using 3D models and drawings, demonstrating the fact that the synthetic process was a necessary part of the design process. BIM models were also used to test ideas against the initially established requirements, such as those related to building energy certification. This corresponds to the testing stage, where the aim is to demonstrate that the product has a desired property or relationship, e.g., that a new building under design would meet the requirements for a B energy performance certificate. Also, although the architect and engineers were not observed to discern the different types of mental and practical activities undertaken, different types of activities must have guided the movement between different stages of the design.

Aspects related to the design constraints were identified. Although many requirements and constraints were established at the beginning of the project, the architect introduced new ones during the solution framing. The function of these constraints was to limit the possible solution space. For example, the architect added the following constraint: the size of the windows at the front of the building would be limited by the size of the transportation door to assure an aesthetically more pleasing solution.

In conclusion, the case supports the idea that designing means designing for humans with humans using different methods/tools to meet functional requirements, as the design process involved many discussions among design team members, and they made frequent use of different methods (e.g., energy simulations, structural calculations, BIM). Furthermore, a clear articulation of the project value structure regarding targets and constraints facilitated communication and the iterative design process. However, in this project, little attention was paid to the design management, and this led to the concept development stage taking three months more than was initially planned. This might also be considered the main shortcoming of this project. It could at least in part be attributed to the fact that the design team had not been working on the project full-time.

As a general rule, design management aspects must also be considered, including, for example, the implementation of the Last Planner System to define information flows and thus facilitate the planning, execution, and control of the design process (Ballard 2000). The other reason why this is particularly important is that currently architects still tend to rely on assumptions instead of involving downstream engineers immediately in concept development. The team also noticed that systematic approaches tend to be resource intensive, and systematic approach is currently not a typical practice in the early stages of design.

6.2 Case Study II: Improvement of Energy Efficient Design of Buildings

This case study aims to use the design of energy and cost efficient buildings as an example to evaluate the usefulness of the new design model. The intention is to highlight the methodological aspects of the conceptual design process in the designing of energy and cost efficient buildings. The proposed process structure embedded in the new design model was used as an integrative framework for aligning the usage of design methods and tools. The initial data for this case study was collected in 2015 and published by Pikas et al. (2015).

6.2.1 Literature Study of Problems and Gaps Related to Energy Efficient Design of Buildings

First, the research relevance was established by a literature review of problems and gaps related to the energy and cost efficient design of buildings. Buildings are designed and built to provide shelter for human activity while meeting a set of requirements and providing a certain level of service to fulfill user needs (Christen et al. 2016). The user expects the product to possess a wide range of qualities – buildings need to be useful, usable, and desirable.

When designing new facilities, most critical decisions are made in the early stages of design, influencing what targets or energy certification levels can be obtained. McLeamy's curve is often used to explain and describe the Pareto principle of 20% decisions affecting 80% of the design work downstream (Eastman et al. 2011; McLeamy 2004).

New sustainability and energy efficiency directives and legislation have induced the need to deliver better performing buildings (Council 2012; Economidou et al. 2011; EU and Council 2018), influencing the way buildings are designed and constructed. Attainment of the nearly Zero Energy Building (nZEB) class requires the inclusion of energy performance-based goals in the early stages of design alongside the architect's consideration of building functions and aesthetics. It is recognized that achieving nZEB requires the use of two broad strategies: minimizing energy consumption through passive energy-efficient measures (Capeluto and Ochoa 2014), and using efficient technologies and local energy production to reduce the amount of energy delivered to the site (Li et al. 2013). However, the typical approaches to the design of sustainable and energy efficient buildings are focused on either the architectural or engineering aspects (Zuhaib et al. 2016). In the former case, this means the focus is on the design and optimization of form (geometry) and function; in the latter case, on the configuration of energy-related systems and components.

The analytical unit in the conception of energy efficient buildings includes the site and systems as a whole. In the context of the design of energy efficient buildings, this requires architects and engineers to understand the energy needs for space heating, cooling, lighting, and hot water consumption and energy uses by the systems and energy sources. The latter is required to understand what type of energy can be delivered and exported to and from the site, including electricity, district heating and cooling, and different kinds of fuels (renewable or not).

For example, by definition, it is necessary to use effective architectural (passive) solutions combined with efficient equipment and on-site renewable energy production to obtain nZEB certification class (Kurnitski and Group 2013). A broad set of design alternatives thus need to be studied and evaluated, making it a laborious task.

The system boundaries and technical elements for nZEB buildings were defined by Kurnitski (2013), as illustrated in **Figure 19**. The figure describes the problem and solution framing for the design of energy efficient buildings, and from this, the steps can be derived for the calculation of the primary energy class, proceeding from the energy needed to heat and cool the spaces and heat water to the final system boundary of the delivered and exported energy.

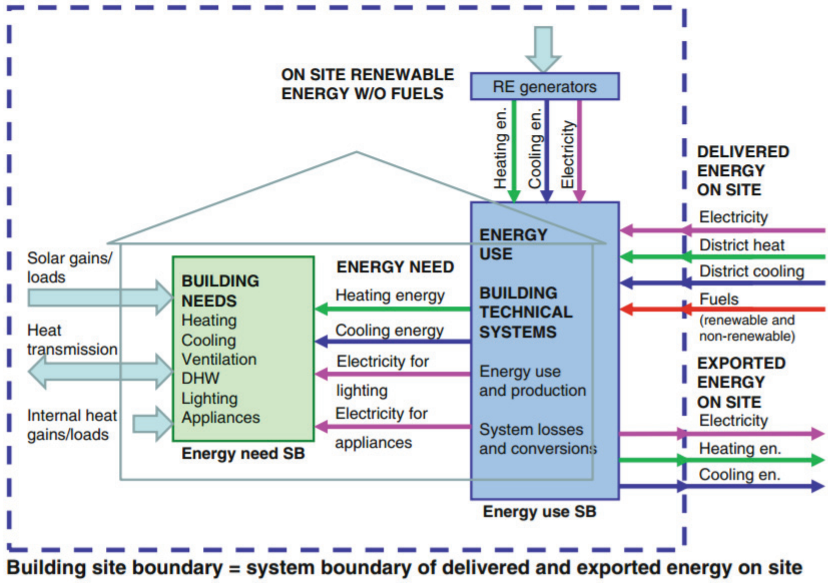


Figure 19. An illustration of the technical definition of nZEB and system boundaries: site boundary for delivered and exported energy, energy needs and use (Kumitski 2013).

However, buildings can cease to meet the requirements for a variety of reasons: purposes and/or use functions can and do change (Andreasen et al. 2015); value is lost due to poor design and construction processes, resulting in product and process variation (Howard et al. 2014; Taguchi and Rafanelli 1994); and artefact components deteriorate over time (Lee 2003; Suh 2001). Thus, relatively often, proposed solutions do not meet energy efficiency class requirements at the end of the first design iteration. As a significant amount of project resources have already been committed, the first step in re-design is often focused on finding creative workarounds to solve unmet performance goals. Thus, the typical procedure or steps followed by the building services engineer to improve energy efficiency is as follows (Pikas et al. 2015):

- Identify if more efficient equipment, for instance, heating, ventilation or cooling equipment can help meet the energy certification class requirements.

- If this is not possible, recommend alternative solutions to the architect that have minimal impact on the architectural solution (e.g., better windows, more insulation, etc.).
- If the energy efficiency level is still not achieved, local energy production may be considered to reach the required energy efficiency level.
- If this is not possible, and only in this case, consider redesigning the system as a whole.

The typical strategy for managing the complexity of designing energy efficient buildings is to focus selectively on a limited number of factors and systems, though this often leads to a neglect of the interdependencies between different decisions and control factors (Arroyo 2014). The hidden assumption is that by optimizing each part (design, construction, and operation) and component (e.g., structural, mechanical, electrical, and interior), the whole can be optimized. This strategy is evident in architectural design guidelines (DeKay 1999; Smith-Masis et al. 2011).

However, relying only on abstractions in analysis and not taking into account other relevant parameters in synthesis can lead to solutions or concepts that are not conceivable down-stream. This has led to a situation where the design for energy efficiency and sustainability has been left at the building systems level, taking a back seat to many other drivers of the design and construction process (AIA 2012).

Adding to this complexity is the recursive nature of design inquiry. Attia et al. (2012) described this as performance driven design subject to the successive layering of constraints on a building. Attia et al. (2012) divided the conceptual design stage into five sub-phases: (1) specification of performance criteria, (2) generation of ideas, (3) design of building zones-layout, (4) preliminary conceptual design, and (5) detailed conceptual design. Typically, different types of costs have been used as an optimization criteria, e.g., initial capital cost, annual operating cost or life cycle cost, but also energy consumption and environmental impact (Attia et al. 2013).

An integrated collaborative approach that would guide designers is necessary to understand how the form, orientation, programmatic strategies, and other variables affect the project's performance in terms of energy, daylighting, comfort, and other design characteristics (AIA 2012). Design management methods have been proposed that would involve downstream designers in the early stages of the design process to solve the problem of misalignment between different design disciplines.

Zeiler and Savanovic (2009) developed a theoretical approach to collaborative design, integral morphological CK (Concept-Knowledge). It is a combination of different theoretical conceptualizations of design, including design morphology, C-K design theory (Hatchuel and Weil 2003), and design collaboration. They recommended the use of the integral morphological C-K design approach in multidisciplinary conceptual building design to 'bridge' the gap between architectural elements such as shapes and materials and indoor climate issues such as overheating and ventilation. Morphological charts are used to visualize solution alternatives in the work of multidisciplinary design teams.

Another method used in lean design is choosing by advantages (CBA), which is driven by the principles of concurrent engineering and collective decision making. Selection is made from among alternatives by considering their relative advantages (Arroyo et al. 2016; Kpamma et al. 2016). In CBA, different strategies are employed to preclude the making of assumptions. For example, benefits of the alternatives being considered are determined individually first and then differences are discussed in the group to expose unfamiliar perspectives or avoid giving undue weight to particular attributes. However, according to Arroyo (2014), CBA also has several limitations that need to be taken into account:

- CBA does not provide insight into the consideration of uncertainty in the attributes of alternatives;
- CBA does not offer guidelines for understanding possible interrelations between factors or criteria;
- CBA may be impractical when evaluating an infinite number of design options; and
- CBA does not provide explicit instructions on how to avoid cognitive biases in decision-making.

The first three limitations can be addressed by implementing more advanced existing engineering methods, such as the Taguchi methods (Taguchi et al. 2005). The last limitation can be addressed by developing better methods, taking into account the psychological aspects of working individually and in teams.

Building information modelling (BIM) has been recognized as one of the essential technologies addressing problems of fragmentation in the construction industry. This means that “BIM is not just a tool, but also a process that enables and even requires new ways of thinking and working together” (Dave et al. 2015; Sacks and Pikas 2013). BIM is a technology expected to support and facilitate close collaboration between project partners (Forgues et al. 2009; Thomson et al. 2009).

In summary, the two broadly used approaches to the design of energy and cost efficient buildings are the technical and architectural strategies. However, the focus tends to be on technical design – optimization of the ‘late’ design parameters, including systems, controls, envelope, and renewables. Designing buildings to meet nZEB requirements is a complex task not achievable by any single discipline, given the definition of technical nZEB and system boundaries. The problem with the technical approach is that decisions regarding functionality, form, and geometry have already been made, and the technical design can only focus on local improvements of the designs. The problem with the architectural approach is that architects often lack the prerequisite knowledge to make informed assumptions regarding technical systems. Therefore, there is a need for a more comprehensive view of how to design and manage the design process to ensure the development of socially, environmentally, and economically viable solutions. This requires the alignment of architectural, technical, and managerial strategies towards the achievement of the required level of building performance.

6.2.2 Case Study Method

The first version of this case study was published by Pikas et al. (2015). Here, it is reinterpreted in terms of the new design model and methods. The particular methods investigated in this study are the following: the morphological design method (Zeiler and Savanovic 2009), the Taguchi robust engineering method, (Taguchi and Clausing 1990) and BIM (Eastman et al. 2011). During the conceptual design process, many other aspects also need to be addressed, but this study focused on the energy and cost efficient design of buildings.

Of the two case buildings described by Pikas et al. (2015), the seven floor building (shown in **Figure 20**) was chosen. This building was selected due to its interesting shading solution using balconies. In the original study, the focus was on the optimization of design parameters to ensure compliance with the targeted energy certification level and cost optimality requirements, instead of on the selection of building systems. This means that designs were limited by the decisions made in the upstream design stages.

Figure 20. A simulation model for the selected apartment building (Pikas et al. 2015).

As the details of the selected building case were already published in the original study, the chosen building is only briefly described here. The main characteristics relevant to this study are summarized in **Table 13**. Most of this data was taken from the detailed area plan, which in addition to the owner's requirements is another typical set of starting-points for the conceptual design stage. Thus, as in the method of design, an assumption about the problem to be given was made. Other relevant research materials and methods used in this case study are summarized in Appendix III.

Table 13. General characteristics of the chosen building.

Description	Requirements and targets
Location and coordinates	Tartu, Estonia (58.36 N, 26.74 E)
Lot area	2736 m^2
Intended use/purpose	100% residential land
Max number of buildings on a lot	1 main building
Max building footprint	700 m^2 (19m x 37m)
Allowed number of floors	6…8 floors
Max relative building height	27 m
Allowed roof incline	0…25 degrees
Min building fireproofing class	TP1 (fireproof structures)

The practical study, i.e., the design of the intervention, its implementation, and evaluation, involved the following steps:

1. Design of the case study intervention.
2. Definition of ideal functions based on given customer and local government requirements.
3. Generation and selection of a set of possible concepts.
4. Implementation and construction of two alternative concepts to be modelled and simulated using energy performance software to identify cost optimal solutions.
5. Application of robust engineering principles to evaluate the sensitivity of selected concepts.
6. Evaluation of case study outputs, comparison with the built designs and results, and results of the case study published by Pikas et al. (2015).

6.2.3 Intervention Design and Implementation

In the conceptual design stage, the focus shifts from the goals, ways of use, and functional and performance requirements to the conceptual design of building sub-systems. Designers and engineers need to deliberate (generate, study and evaluate) the selection of solution strategies that would bind downstream decisions, i.e., regarding benefits, challenges, and issues, such as sensitivity to control factors or the interdependencies between design decisions. The steps followed in the design of the intervention and conceptual design of energy and cost efficient buildings are described below.

Intervention Design

In this sub-section, the new design model developed in Chapter 5 is transformed into a form suitable for this case study. Three simplifications are made due to the particular focus of this case study. First, although no design process is linear, the steps taking a design from one state to the next are depicted sequentially in **Figure 14**. Secondly, the stages related to problem and solution framing are merged with the stages related to delivery and evaluation. While this does not mean that there will not be re-interpretations of what is given and sought, the problem and solution framing (invention stage) are assumed to be given in the conceptual design. The delivery stage in the design context involves the presentation and justification of solutions by the designer to the building owner and evaluation by the owner. This would take place, for example, in dynamic client briefing and evaluation meetings (Jensen 2011). Thirdly, as the consideration of details and components has a marginal influence on the conceptual design, this is merged with the implementation stage. For example, **Figure 20** shows how few details are needed to run the energy simulation. Roof, wall, and window elements are omitted, and only surfaces associated with the control parameters are modeled.

The proposed process structure for this case study consists of seven steps (shown in **Figure 14**), instead of the original 13. In each step, the input state is converted to an output state through mental and practical actions, which create relationships between entities within and across domains. Thus, the following sub-sections are structured as following: the first sub-section of 6.2.3 addresses (1) problem and solution framing and ideas and requirements (invention); the second sub-section of 6.2.3 addresses (2) the design concept and (3) design embodiment for the generation of design alternatives; the third sub-section of 6.2.3 addresses (4) implementation and (5) the assembly of design alternatives; the fourth sub-section of 6.2.3 addresses (6) the testing of design alternatives; and the fifth sub-section of 6.2.3 addresses (7) delivery and evaluation.

Next, the different stages and steps in the proposed **Figure 14** are juxtaposed with the three methods and tools. Here, the proposed process structure functions as an integrating framework for the different methods and tools. These methods and tools were addressed in sub-section 6.2.1. The study employed the following methods: the morphological design approach (Zeiler and Savanovic 2009), Taguchi robust design (Lu et al. 2015), and BIM (Eastman et al. 2011).

Zeiler and Savanovic (2009) proposed a process structure with the following steps for the integral morphological design: (1) identification of functions and aspects; (2) generation of sub-solutions; (3) combination and selection of integral design concepts; (4) evaluation and selection of concepts for further design. Here it is proposed to extend these steps from (1) the problem and solution framing to (7) delivery and evaluation.

The Taguchi robust engineering method focuses on the study and analysis of designs. The method consists typically of the following steps (Taguchi et al. 2005): (1) identification of essential quality characteristics (ideal function); (2) selection of the control, noise factor levels, and signal-to-noise ratio; (3) design of an appropriate orthogonal array matrix experiment; execution of the matrix experiment; and (4) evaluation of results and selection of optimal levels for control factors. For a more detailed description of steps see Appendix III. Except for in the concept design and design embodiment stages, where the integral morphological approach is mainly operational, integral morphological design and the Taguchi robust engineering methods can be considered complementary; the former focuses on the generation of holistic solutions, and the latter on the study and analysis of alternatives. It is proposed to extend these steps from the (1) the problem and solution framing (partially) to (7) delivery and evaluation.

BIM has three meanings (Eastman et al. 2011): as a noun, it refers to the digital model of a building; as a verb, it is the process of modelling the building and making use of it in the analysis and communication of solutions. The third meaning is associated with life-cycle building information management. In **Figure 14**, BIM extends from implementation (4) and construction of solutions (5) to testing (6) and delivery and evaluation (7). Hence, BIM is operational during the synthesis.

Table 14. The juxtaposition of the simplified design process model with methods and tools.

Modes of Inquiry	**Analysis**			**Synthesis**			
Stages	1. Problem and Solution Framing	2. Concept	3. Embodiment	4. Implementation	5. Construction	6. Testing	7. Delivery and Evaluation
Input State	Gap	Function	Mode of Action	Embodiment	Assemblies	Sub-Systems	Behavior
Mental and Practical Actions	Intuition, Transformation and Decomposition	Regression and Decomposition	Regression and Decomposition	Communication, Making and Verification	Assembly, Composition and Verification	Testing, Deduction and Verification	Induction, Analogy, Delivery, and Justification
Output State	Goal, Way of Use and Function	Mode of Action	Embodiment	Assemblies	Sub-Systems	Behavior	Operation, Value, and Satisfaction
Methods and Tools		Integral Morphological CK Design Method					
		Robust Design Methods					
				Building Information Modelling			

Problem and Solution Framing: From Customer Voice to Engineering Voice

As an extension of step (1) in **Figure 14**, the objective is to identify the functions and aspects which are critical when designing energy and cost efficient buildings. Requirements flow into the conceptual design from many different places, including building programming and planning, customers and users, and legislation and standards and may be related to customers/user safety, a healthy and hygienic environment, indoor climate, sustainability, energy efficiency, durability, economic construction and operations, aesthetics, and usability. Most of these are directly or indirectly related to the goals of the owner and the nature of the activities to be carried out in the future workplace.

Table 15 summarizes high-level customer requirements regarding the number of floors and apartments, gross area, target cost, and minimum energy performance class. The values were chosen based on the designed and built building. Also, a snapshot is provided of the detailed area plan to help visualize the building footprint, location on the lot, location constraints, footprint and height constraints, and the surroundings (with orientation to true North). The building site, customer and user needs, and legislation mold the design solution space.

Table 15. Summary of generic requirements for designers and engineers.

Description	**Requirements and targets**	**Detailed area plan**
Number of stories, -	7	
Number of apartments	48	
Occupants density, m^2/person	28	
Gross area, m^2	4200	
Construction cost (includes value added tax), €/m^2	900	
Minimum energy performance class (in the Estonian classification)	C	

According to the Taguchi engineering method, the ideal function selected should also be relevant to customer needs. In this study, primary energy use and the 30-year net present value (NPV) were selected as the main ideal functions, calculated according to instructions shown in Appendix III. The NPV as the main ideal function is directly relevant to owners: deviation from the optimal cost solution affects customer satisfaction; i.e., the customer is either overinvesting or has to pay more to keep the building in operation. Thus, ideal performance would be when the building's 30 year NPV is lowest at the targeted primary energy performance level.

Design Concepts and Embodiment

The next step is the movement from requirements to principle solutions and partial solutions, corresponding to steps (2) and (3) in **Figure 14**. The integral morphological method supports the process of defining and developing the design concept(s) systematically and collectively. On the vertical axis of the morphological charts, the functions, sub-functions, and aspects are positioned to establish the general operation of the artefact. On the horizontal axis, possible sub-solutions for the functions and aspects are defined. A completed chart represents a general overview of sub-solutions and potential combinations for the concept design as a whole.

Regarding the collaborative process, Zeiler and Savanovic (2009) proposed that the disciplines involved in the conceptual design should first prepare their individual charts, and then designers with different backgrounds can agree on the elements to be taken from the separate charts to form the morphological overview. In this way, the morphological charts would provide design teams with a visualization of alternatives and facilitate discussion.

A morphological chart from the perspective of energy efficient design that takes into consideration the building context and customer and functional requirements has been defined in **Table 15**. Lighting was excluded from this list, as the designers did not have control over it during the design process. In practice, this means that the owners would be choosing the light fixtures themselves, and lighting would be a source of discrepancies in the simulation of the energy consumption of the building.

The next step is to define general solution alternatives, the combination of different sub-solutions (**Table 16**). This step extends into the synthesis. The first column of the morphological chart represents the first concept (cells shaded light gray), and the second concept is indicated by a circled number two, including the following sub-solutions: rectangular shape without balconies, prefab concrete, isolated and efficient windows, flat roofing, ground heat pump and radiators, mechanical exhaust ventilation, and thermal solar panels. The reinforced cast-in-place concrete structure, strip/tape windows, and grass roof were listed only as potential sub-solutions, as they were not selected as a part of either of the two design solution concepts.

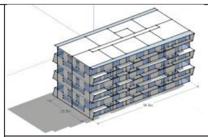
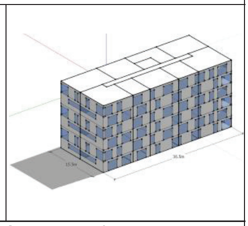
Table 16. The morphological representation of general concepts (the first concept is in the gray-shaded cells; the second is indicated by a circled number two).

Sub-concepts/Aspects	**Sub-Solutions (designs)**	
Shape, orientation, and shading	Rectangular shape with shading	Rectangular shape without shading ②
Materials and structures	Prefab concrete and sandwich wall panels ②	Reinforced cast-in-place concrete structure
Façade/Windows	Isolated and efficient window sizes ②	Strip/Tape windows
Roofing	Flat roofing ②	Grass roof
Heating	District heating and radiators ②	Ground heat pump and radiators
Fresh air	Apartment-based balanced ventilation (rotary heat recovery)	Apartment-based balanced ventilation (cross-flow plate heat recovery) ②
Self-supporting (renewable energy)	Photovoltaic system	Thermal solar panels ②

Implementation and Construction

The definition of the two concepts is followed by implementation and construction, which in **Figure 14** correspond to steps (4) and (5), respectively. This is a movement from the analytical to the synthetic mode of thinking and acting; i.e., the implementation and construction of ideas in accordance with requirements. Cross (2008) defined this step as a 'determination of characteristics' in his design process model, the parametrization or assignment of properties to sub-solutions. For the two concepts presented in **Table 16**, the characteristics of the alternatives are summarized in **Table 17**.

Table 17. Description of characteristics (control factors) and alternatives for the two concepts developed.

First Concept		**Second Concept**	
Rectangular shape with shading		Rectangular shape without shading	
	Shading: South A/H ≥ 0.35; West B/C ≥ 0.35		
	Shading: South A/H ≥ 0.7; West B/C ≥ 0.7		
Prefab concrete and sandwich wall panels (applies to both concepts)			
Insulation thickness, mm	150	210	300
U-value, W/(m^2K)	0.25	0.17	0.13
Area without shading, m^2	1199	1195	1188
Area with shading, m^2	1799	1795	1788
Cost, €/m^2	147.0	153.0	161.9
Isolated and efficient window sizes (applies to both concepts)			
Window type	2 panes 18mm gap with Argon filling	3 panes 18mm gap with Argon filling	4 panes 12mm gap and Krypton filling
U-value, W/(m^2K)	1.13	0.72	0.55
Solar gain g-value,	0.58	0.45	0.34
Area, m^2	669.2	669.2	669.2
Cost, €/m^2	66.6	73.6	204.2
Flat roofing			
Insulation thickness, mm	250	350	450
U-value, W/(m^2K)	0.15	0.11	0.09
Area, m^2	565	565	565
Cost, €/m^2	101.5	106.5	111.5
District heating and radiators (applies to both concepts)			
Heat source (district heating) efficiency, -	1.0		
Heating system (radiators) efficiency, -	0.97		
Apartment based balanced ventilation (rotary heat recovery, first concept only)		**Apartment based balanced ventilation (cross-flow plate heat recovery, second concept only)**	
Ventilation Heat Recovery Temperature Efficiency, %	75/80/85	Ventilation Heat Recovery Temperature Efficiency, %	75/80/85
Minimum exhaust air temperature, °C	0	Minimum exhaust air temperature, °C	5.0
Air flow rate, l/(s·m2)	0.42	Air flow rate, l/(s·m2)	0.42
Air flow rate, l/(s·person)	3.36	Air flow rate, l/(s·person)	3.36
Unit cost, €	1200	Unit cost, €	1300
Photovoltage system (first concept only)		**Thermal solar panels (second concept only)**	
PV System Areas, m^2	100/150/200	Thermal solar collector area, m^2	100/150/200
Number of panels, pcs	61/92/122	Accumulation tank size, l	3000/3750/5000
Panel efficiency, %	17.1	Cost, €/ m^2	564/529/485
Cost, €/kW	1100		

The control factors and noise factors are determined to evaluate the sensitivity of different design concepts to variations. In **Table 18**, control factors and noise factors are summarized. Designers determine the control and noise factors and also forecast their ranges. These ranges can be chosen based on experience, theoretical ranges, or testing. The idea is to choose ranges that have a significant impact on building performance. The chosen noise factors should then be compounded, meaning that extreme conditions are assumed.

Table 18. Summary of control and noise factors as an input for the evaluation of the robustness of both concepts.

Parameters		Level 1	Level 2	Level 3
Control factors	South and west orientation shading	No shading	South A/H ≥ 0.35; West B/C ≥ 0.35	South A/H ≥ 0.7; West B/C ≥ 0.7
	Ventilation heat recovery temperature efficiency, %	75	80	85
	Prefab concrete and sandwich wall panels U-value, W/(m² K)	0.25	0.18	0.13
	Isolated and efficient window sizes U-value, W/(m² K)	1.13	0.72	0.55
	Flat roofing U-value, W/(m² K)	0.15	0.11	0.09
	*PV System Area, m²	100	150	200
	* Thermal solar system area, m²	100	150	200
Noise factors	Solar collector production used on site, %	40	60	80
	PV production used on site	59.4	74.4	89.4
	PV panel or thermal solar panel shading factor, -	0.6	0.8	1
	Minimum Exhaust Air Temperature Setpoint, °C	-5	0	5
	Space Heating temperature setpoint, °C	21	22	23
	Window opening temperature setpoint, °C	No Opening	25	23.5

The type of signal-to-noise (S/N) ratio needs to be selected based on the behavior of the ideal function. S/N is an index used to assess the quality of designs and find the combination of factors that are the least sensitive to selected noise factors. Standard output response applications for which the S/N ratios have been determined are the nominal-is-best, smaller-is-better, and larger-is-better. The higher the S/N ratio, the more robust the design, or in other words, the higher the quality (Wu and Wu, 2000). In the current study, the performance of the design is ideal when the 30-year NPV is the lowest. Therefore, the appropriate output response type in the current case is the adjusted nominal-is-best (Wu and Wu 2000):

$$S/N = 10log\left(\frac{\bar{Y}^2}{s^2}\right) \quad (1)$$

where $\bar{Y}^2$ is the sum of the squares of arguments (y_1, y_2, ..., y_n) and s^2 is the standard deviation.

The next step in the Taguchi method is to assign control and noise factors to the orthogonal array for the parameter design and evaluation of robustness. The control factors are placed on the inner array, and the noise factors on the outer array. The selection of an orthogonal array is based on the number of factors and their levels. In this study, there were six control factors and five noise factors for both concepts. An orthogonal array with L_{27} = 27 experiments was chosen given the number of factors and their levels (Wu and Wu 2000). The 27 experiments with the control factors were assigned to the inner array, and another 27 experiments with the noise factors were assigned to the outer array. Thus, a total of 729 simulations for each concept were conducted. IDA-ICE simulation software was used to conduct the simulations (IDA-ICE 2014).

Testing: Robustness Analysis of Two Design Concepts

The next step (step (6) in **Figure 14**) is the deduction of the behavior of the developed building concepts. During the conceptual design stage, the robustness of the alternatives is evaluated at the building systems level. The S/N ratio was calculated using Minitab software (Minitab 2018). The results of the robustness analysis for the first concept using an ideal function based on primary energy use are depicted in **Figure 21** (a) and (b), and one based on a 30-year NPV in **Figure 22** (a) and (b).

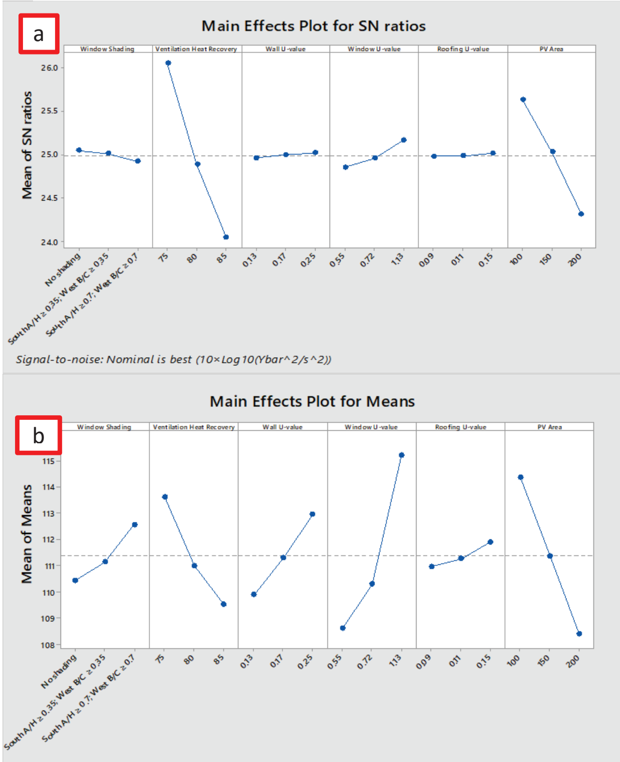
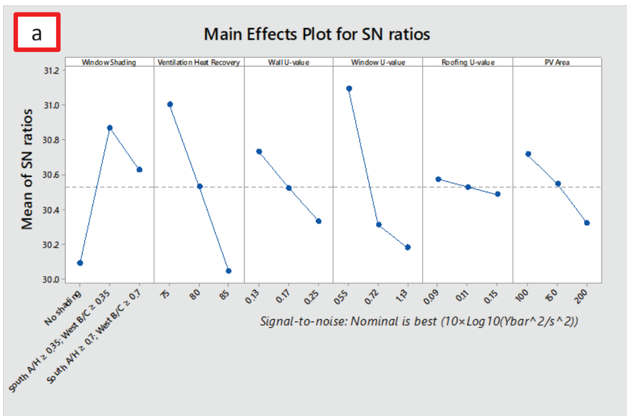


Figure 21. The primary energy robustness analysis for the first concept: (a) the average S/N values for different levels of control factors; and (b) the average effect of control factors on mean values.



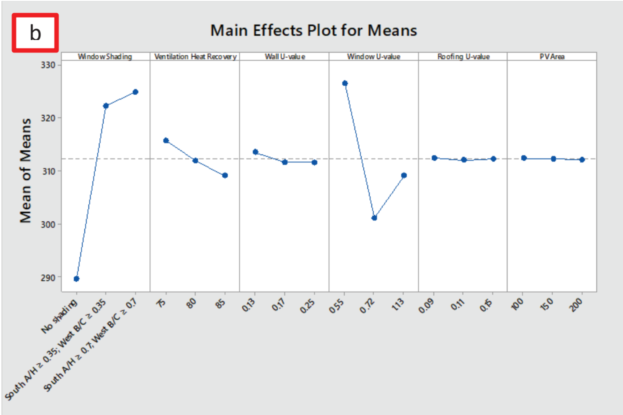


Figure 22. The 30-year NPV robustness analysis for the first concept: (a) the average S/N values for different levels of control factors; and (b) the average effect of control factors on mean values.

Next, a two-step selection process is followed. First, control factor levels should be selected from the response figure that have a higher S/N ratio to reduce deviation from the average. Secondly, control factors whose level changes do not have a substantial effect on the S/N ratio but do affect the average should be selected so that the mean is brought closer to the target. These steps are first applied to the primary energy based selection of control factors and then to the 30-year NPV based selection. According to the robust engineering analysis, the following levels for different control factors should be selected:

- Window shading: no shading leads to higher robustness in primary energy, but according to the 30-year NPV, it would be reasonable to choose South A/H ≥ 0.35 levels of shading; West B/C ≥ 0.35. However, as the aim is to reduce primary energy use at a reduced cost, then no shading is a better choice.
- Ventilation heat recovery: according to primary energy S/N, 75% should be selected, though according to the means, an 80% heat recovery is closer to the average of the means, and the same can be concluded based on the 30-year NPV.
- Wall U-values: according to primary energy, wall U-value is only slightly dependent on the selected noise factors but influences primary energy S/N. Thus, it would be reasonable to select a wall U-value equal to 0.13 W/(m^2 K), though according to the 30-year NPV, it would be better to select 0.17 W/(m^2 K), since there is no cost difference between it and the lowest U-value, and it is still relatively robust.
- Window U-values: according to primary energy, it would be reasonable to select the lowest U-value, though based on the 30-year NPV, it would be reasonable to select 0.72 W/(m^2 K), which should be cost optimal over 30 years.
- Roof U-value: the roof has little impact on primary energy and 30-year NPV. Thus, the same logic that applies in the case of wall U-values applies here. However, according to the 30-year NPV, it would be better to

select a U-value that is less expensive and apply the savings to other factors of the design. Thus, 0.11 W/(m² K) is selected. The same conclusion was drawn in the original study (Pikas et al. 2015).

- PV Area: with regard to primary energy, PV has a linear relationship between different level factors in S/N and primary energy, though according to the 30-year NPV, it has little impact on life-cycle costs. It would thus be reasonable to choose 150 m² of panels.

The results of the robustness analysis of the second concept with primary energy as the ideal function are depicted in **Figure 23** (a) and (b), and with the 30-year NPV as the ideal function in **Figure 24** (a) and (b).

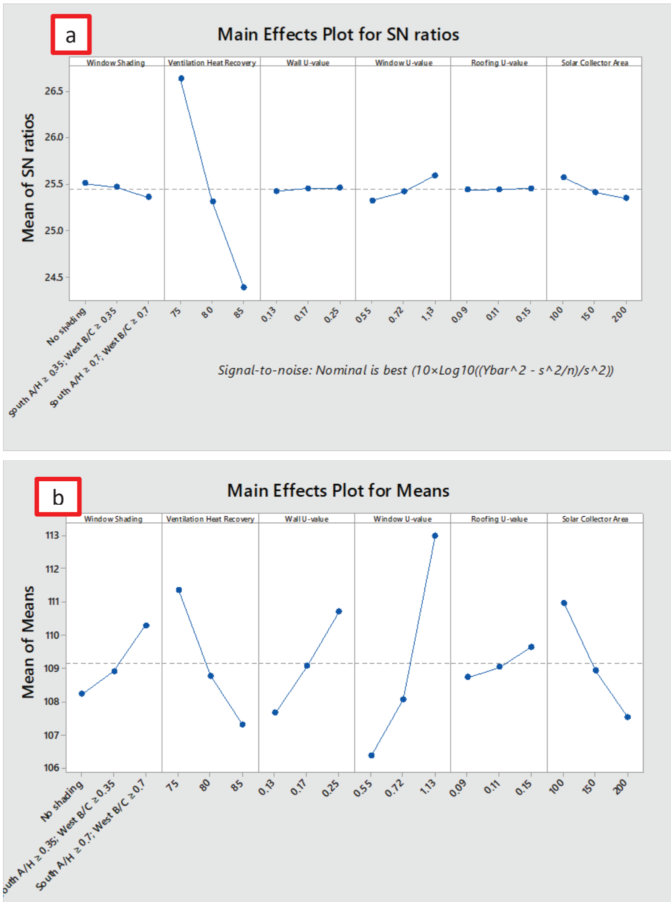


Figure 23. The primary energy robustness analysis of the second concept: (a) the average S/N values for different levels of control factors; and (b) the average effect of control factors on mean values.

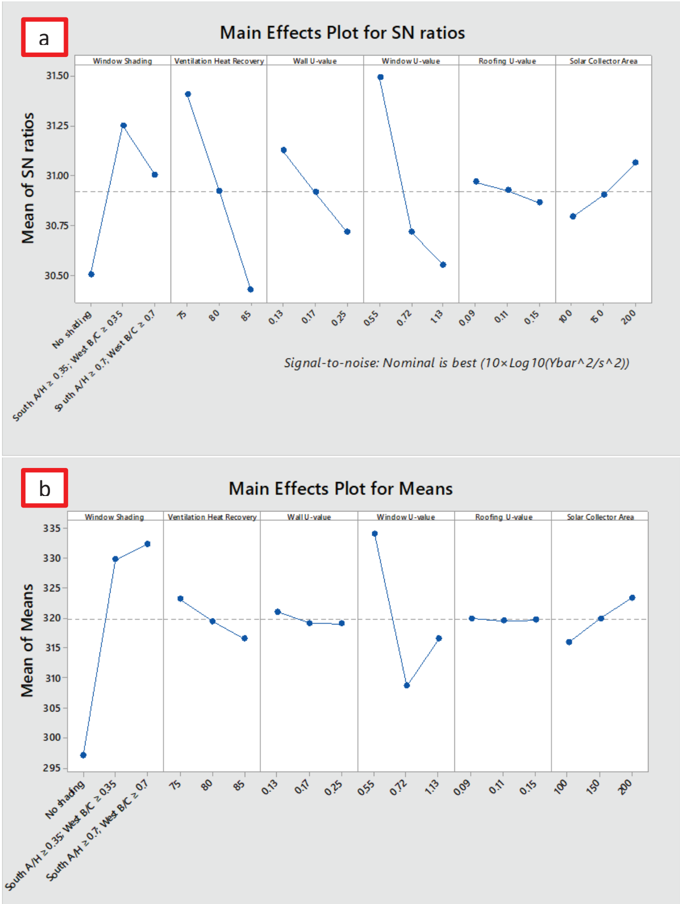


Figure 24. The 30-year NPV robustness analysis of the second concept: (a) the average S/N values for different levels of control factors; and (b) the average effect of control factors on mean values.

According to the results, the following levels for different control factors should be chosen:

- Window shading: regarding the shading, the same logic applies here as in the case of the first concept. No shading is relatively robust but has a significant impact on the cost. No shading leads to the lowest 30-year NPV.
- Ventilation heat recovery: according to primary energy S/N, 75% should be selected, though according to the means, an 80% heat recovery is closer to the average of the means, and the same can be concluded based on the 30-year NPV.
- Wall U-values: according to primary energy S/N, wall U-values are only slightly dependent on the selected noise factors but influence primary energy. Thus, it would be reasonable to select wall U-values equal to 0.13 W/(m^2 K), though according to the 30-year NPV, it would be better to select 0.17 W/(m^2 K), since there is no cost difference between it and the lowest U-value, and it is still relatively robust.

- Window U-values: according to primary energy S/N, it would be reasonable to select the best U-value, though based on the 30-year NPV, it would be reasonable to select the cheapest, a value of 0.72, as it should be cost optimal over 30 years.
- Roof U-value: as in the case of the first concept, the roof has little impact on primary energy and 30-year NPV. Thus, the same logic that applied in the case of wall U-values applies here. However, according to the 30-year NPV, it would be better to select a U-value that is the least expensive (0.11 W/(m² K)) and apply the savings to other factors of the design. The same conclusion was drawn in the original study (Pikas et al. 2015).
- Solar Collector Area: with regard to primary energy, the solar collector area exhibits a linear relationship between different level factors in S/N and primary energy. At the same time, according to the 30-year NPV, it has little impact on life-cycle costs, and it would be reasonable to choose 150 m² of solar collectors.

In **Table 19**, the selected factor levels are summarized. Overall, the solutions selected for concept 1 with PV panels are similar to those selected for concept 2 with thermal solar panels. In the evaluation and discussion sub-section, the overall merit of the two concepts needs to be assessed.

Table 19. Summary of selected factors for two concepts.

Parameters		Concept 1	Concept 2
Control factors	South and west orientation shading	No shading	No shading
	Ventilation heat recovery temperature efficiency, %	80	80
	Prefab concrete and sandwich wall panels U-value, W/(m² K)	0.17	0.17
	Isolated and efficient window sizes U-value, W/(m² K)	0.72	0.72
	Flat roofing U-value, W/(m² K)	0.11	0.11
	*PV System Area, m²	150	-
	* Thermal solar system area, m²	-	150

Evaluation

The next step, corresponding to step (7) in **Figure 14**, is to evaluate the results. The results of the robustness analysis make it clear that different combinations of control factors respond differently to noise factors. Some control factors are more sensitive than others; i.e., not all control factors studied here had a direct impact on the 30-year NPV. Only shading, ventilation recovery, and windows had a significant impact on the 30-year NPV. Furthermore, although renewable systems led to better primary energy use, these are highly sensitive to noise factors.

From the perspective of robust engineering, the selected low-sensitivity system would be the one with no shading, 80% heat recovery, U-values of 0.17 W/(m² K) for walls, 0.72 W/(m² K) for windows, and 0.11 W/(m² K) for the roof, and 150 m² of PV panels, resulting in an average of 108.8 kWh/a m² with a standard deviation of 6.01 and a 30-year NPV of 277.38 €/m². The same combination was chosen for concept two with solar panels, resulting in an average of 106.4 kWh/a m² with a standard deviation of 5.66 and a 30-year NPV of 285.1 €/m². Although the solar collector system had better primary energy use on average, its 30-year NPV is remarkably higher due to the higher upfront investments and the sensitivity to variation.

The results for both concepts illustrate the importance of using a balanced strategy when designing energy and cost efficient buildings. For example, a system with poor passive solutions but a larger photovoltaic capacity is more sensitive to external noise factors. If one of the assumptions made in the design proves to be incorrect, the actual energy performance of the designed system can vary remarkably, as evidenced by the many studies on design errors and problems (see Chapter 1).

In the original study by Pikas et al. (2015), two built apartment buildings were studied in-depth. Solutions were developed to meet the targeted nZEB requirements, low energy building requirements, and cost-optimal minimum energy performance requirements. The financial feasibility of solutions was assessed using the EU NPV methodology, assuming a 30-year period. This resulted in optimal energy efficiency levels of approximately 110 kWh/m^2. In this study, similar results were obtained: 108.8 kWh/a m^2 and 106.4 kWh/a m^2 as the cost optimal levels for concept one and concept two, respectively. Thus, only marginal improvements on the results reported in the original study were made. Compared to estimates for the built apartment building, remarkably better results were achieved at the same investment level. In the built apartment building, the estimated primary energy use was ca. 138 kWh/a m^2. Thus, in this study, a solution better by about 30 units was achieved.

However, the most significant difference between the original study by Pikas et al. (2015) and this reinterpreted study is that possible sources of variation were investigated in-depth, enabling designers to make better, more informed decisions. This is a noteworthy matter, considering that many studies have recognized that the problem with designing energy and cost efficient buildings is that the designed energy performance of a building almost never corresponds to actual energy performance (Kalamees et al. 2012; Kalamees et al. 2014; Kõiv et al. 2014; Pikas et al. 2014; Pikas et al. 2015; Ryghaug and Sørensen 2009; Sunikka-Blank and Galvin 2012). This problem is rooted in the fact that many assumptions regarding the building yet to be built are made during the design process, especially in regard to its environment (e.g., occupancy-related factors), leading almost invariably to unmet energy performance requirements.

6.2.4 Discussion and Summary

In this case study, the aim was to develop an understanding of the methodological questions involved in the designing of energy and cost efficient buildings and the usefulness of the new design model. More specifically, it was to explain the steps involved in the conceptual design of energy efficient buildings and the relationships between different steps. The new design model was used to align different contemporary design methods and tools, including the integral morphological C-K design method, Taguchi robust engineering, and BIM.

From the start of the conceptual design process, it is important to listen to the client and transform the voice of the client into the engineer's voice. When deciding on the criteria that will guide the design process, designers should choose an ideal function suited to the requirements of the building owner, who is the ultimate judge of design quality. In this study, in addition to primary energy use, the 30-year NPV was chosen as an ideal function, as deviation from the cost optimal point has a direct impact on the building owner, in terms of either the initial investment or building operation costs.

The ideal functions together with the identified sub-functions should guide the generation of partial solutions and design concepts on a system level. As the proper functioning of the artefact as a whole depends on the design sub-solutions and configurations, it is critical to involve all the relevant design disciplines in the design process. The design of energy and cost efficient buildings is a multidisciplinary task. All the different perspectives should be taken into account when design concepts are generated, judged, evaluated, and selected.

The integral morphological design method provides the structure for the collaborative design process. However, the evaluation and selection of final combinations of control factors should not be made without an understanding of the energy performance of the building designs. The Taguchi robust engineering method is complementary in function to the integral morphological design method. The selected combinations should be studied rigorously to understand their effect on the ideal functions. When the performance of design concepts is tested, the output is a characterization of the behavior of control factors with respect to mean and signal-to-noise values of the ideal functions. What is the expected level of quality or deviation when achieved values are compared with energy and cost optimal solutions? Thus, the final selection of the levels for control factors needs to be made based on the tests, requiring judgment and evaluation by the designers. In this process, BIM is used to facilitate the representation of the designs and communication among team members.

Results for the energy efficiency and cost optimal designs of the building were significantly better than the figures for the constructed facility and some ways also better than those reported in the original study by Pikas et al. (2015), as more informed decisions could be made related to the sensitivity of the design concepts to noise factors.

Furthermore, based on the results of this case study, a recommendation can be made to companies developing software for dynamic energy simulations. These companies should add functionality that makes it possible to assess the impact of variations in internal and external noise factors on building performance. This would help designers and energy specialists design more robust buildings, less subject to noise from different sources.

Finally, although there is still a need for the collaborative interpretation, generation, judgment, and evaluation of design concepts, conceptual design is primarily focused on the technical aspects of building structures – causal considerations in design.

6.3 Case Study III: Improvement of Design and Design Management Practices

The third study is a longitudinal case study involving participative action research focused on the design of practical interventions. The study lasted from spring 2016 until the end of 2017. From the point of view of the present thesis, this study is an instantiation of the new design model in the design management context to improve design processes.

The Estonian design organization in this case study, founded in 2005, provides multiple design services, all building design services and design project management services. In 2015, half of the projects were public design projects, the other half private design projects in either Estonia or Scandinavia (primarily, Norway). In 2016, a strategic decision was made not to participate any longer in public procurement projects. Thus, by the end of 2016, the portfolio of projects consisted mostly of private projects. A similar trend continued in 2017. The organization had been using building information modelling (BIM) for the previous nine years, and by this time all projects, no matter the size, were being completed using BIM. As of 2018, a total of about 40 people were working in different divisions of the organization.

For the company, the primary success criteria for the implementation of the case study project was an increase in the overall capability of delivering design projects and in their quality. The case study and data collection methods, the design of the intervention, its implementation, and its evaluation are described below.

6.3.1 Case Study Method

In this study, the usefulness of the new design model in improving design and design management practices is evaluated. The research process was structured according to the (participative) action research methodology. However, it was not typical action research, as the emphasis was on the development of practical artefacts with a view to the integration of the technical and social views of design and design management processes. Thus, some inspiration for the structuring of the case study work came from design science research (Kuechler and Vaishnavi 2011). Both action research and design science research are methodologies for developing scientifically grounded solutions for problems with theoretical and practical relevance. The following is an outline of the research phases (Susman and Evered 1978):

- **Diagnosing as-is situation:** Divided into three sub-steps, this phase is concerned with establishing the proper understanding of 'as-is' situation and problems with theoretical and practical relevance. A good understanding of the problems forms a starting point for designing, implementing and evaluating interventions. Thus, as in Aristotelian epistemology, the starting point for the case research should be the material world (design office), but not the world of ideas (concepts and theories).
- **Intervention design and action planning:** Here, the research process deviates from traditional action research methodology, as it also has elements of design science research. The emphasis is placed on the instantiation of practical artefacts based on the new design model.
- **Implementation of design artefacts through action taking:** In this phase, the focus was on the implementation of design artefacts through practical action, i.e., the new artefacts and process descriptions

developed became the basis for change management. This was accomplished in two iterations in collaboration with key members of the design office. The first iteration was carried out in autumn 2016, the second iteration in summer 2017.

- **Evaluation of interventions:** The impact of new interventions were continuously evaluated throughout the two iterations. Formal written interviews and focus group interviews were used to evaluate the impact of the interventions.
- **Clarification of lessons learned:** Lessons learned were summarized in the case study discussion and summary sub-section. These are generalized evaluative statements about the effects of the interventions, developed based on the new design model and design management concepts.

Research Methods

The diagnosing of the ‘as-is’ situation was divided into three steps. In each step, different methods were used to collect and analyze data: 1) surveys and interviews to understand the views of designers and engineers on the main challenges; 2) a database analysis based on data from the enterprise resource planning (ERP) system; 3) observations of design projects to gain contextual understanding of the problems and challenges.

A survey form, compiled in Google Forms, was sent to 34 designers: 10 architects, 12 structural engineers, 8 building services engineers, and 4 project managers. A total of 24 people responded, representing a response rate of 70.5%. In the survey, respondents were asked to assess design management and organization issue statements on a five-level Likert scale from strongly disagree to strongly agree. The results were analyzed and summarized for the group as whole, by discipline (6 architects, 7 building services engineers, 7 structural engineers, 4 project managers), and by years of work experience (three respondents less than 2 years, ten 3-5 years, four 6-9 years, four 10-14 years, and four 15+ years). The survey questions and statements can be found in Appendix IV.

The design office had been using an ERP system for the previous seven years. This made it a useful resource when doing the retrospective analysis of past projects. When carrying out the database analysis, the following questions were posed: What type of projects had been completed and how successful were they? How well were they able to plan and execute their projects? Where was the time spent in the design process? How much resources were expended on fixes, changes, and meetings before and after the project contract deadline?

When querying the database, the following criteria were selected: the design office had a minimum of two disciplines working on the project; at least two stages out of the typical four (schematic design (SD), preliminary design (PD), design development (DD), and construction documents (CD)) were carried out; projects were executed between January 2014 and September 2016. Data for 28 projects was analyzed: ten residential buildings (35%), five industrial and warehouse buildings (18%), four office and four public buildings (14%), two commercial and two infrastructure facilities (7%), and one industrial and office project

(5%). A total of 13,421 data points (activities) accounting for a total time of 51,357 hours were exported to Excel for statistical analysis.

Project observations can be divided into two categories, the observation of a single project over eight weeks and the observation and analysis of communication practices in two different but related projects. The latter two projects were ordered by the same client and had almost the same delivery team.

The objective of the observations, conducted over eight weeks, two days a week, between 5.7.2016–1.9.2016, was to get a contextual understanding of design and design management problems. A few interventions were introduced to collect data, including the co-location of nine out of ten (three architects, four structural engineers, and three building services engineers) design team members from different disciplines and twice-a-week stand-up meetings. Designers and engineers were observed from morning until evening, and all work activities and communications were recorded.

In the intervention design and action planning phase, the focus was on designing practical support for design and design management in the design office, incorporating insights on lean design management.

The implementation of design artefacts through action was carried out in two iterations together with key members of the design office: two board members, three heads of functional departments (one from architecture and one each from structure services and building services), one project manager, and two senior architects/engineers (one architect and one engineer). Newly designed artefacts, for example, the process descriptions, became the basis for the incorporation of several methodologies, methods, and tools. The first design iteration was carried out in autumn 2016, the second in summer 2017.

In the first iteration, the development of managerial practices and solutions was approached primarily from the perspective of the practical problems of the organization. The stages and causal structure of the new design model were used as a mental framework for how the 'to-be' processes would need to look. After a few months of design sessions and partial implementation of interventions, a written email-based interview was carried out with the quality management team to evaluate the impact of the proposed solutions.

The logic of the organization of the second iteration, steps involved, inclusion of design staff, and evaluation, was similar to that of the first iteration. In the second iteration, the main focus was on design management. At the first meeting, as each team member shared his or her views on current practices, it became apparent that there were significant differences in opinion among participants. At subsequent meetings, three value stream mapping events were carried out to devise a new first and second level process model. Each meeting concluded with a discussion on lessons learned.

At the end of the second iteration, a focus group meeting was organized to evaluate the impact of changes in the company. Participants were invited to take part in the focus group by e-mail; relevant information regarding its purpose and general guidelines were also included. Besides the design staff who had been involved in the iteration, a few additional staff members were included in the focus group (one project manager, and one engineer), bringing the number of participants to 10. The author of this thesis facilitated the focus group meeting. The participants of the focus group meeting were divided into three groups of three or four persons and asked to evaluate the impact of the interventions in the company.

To complement the evaluation based on the focus group interviews, a general analysis of projects begun after the introduction of the interventions and completed before the end of this research project was conducted. When querying the database, the same criteria were used in the as-is situation analysis. Data for a total of 10 projects was analyzed: three residential buildings (30%), one industrial and warehouse building (10%), two public buildings (20%), two commercial buildings (20%), and two infrastructure facilities (20%). A total of 2,654 data points (activities) representing a total time of 15,297 hours were exported to Excel for statistical analysis.

6.3.2 Diagnosing As-Is Situation

As was described in Chapter 1, technical and managerial problems are commonplace in building design and design management. However, these problems are often described at a very abstract level. Thus, with a view to developing a contextual understanding of these problems, the first phase involves diagnosis of the 'as-is' situation, i.e., the identification of relevant practical problems with potential for theoretical contributions.

Survey and Interview Results

The survey results are summarized in **Figure 25**. If designers had more time, they believe that better design projects could be delivered. Also, they know where things go wrong and why, indicating that designers/engineers believe that design practices can be improved. As for the problems, the main ones were considered to be poor coordination, inherent uncertainty in information flows, and the lack of timely responses from clients.

Figure 25. Summary of results of survey on design management and organizational issues in the design office (0 - strongly disagree to 5- strongly agree).

At the same time, responses varied according to the respondent's years of work experience and discipline. The more experienced the designer/engineer seemed to be, the more confident he or she was about knowing where, when, and why projects go wrong. For experienced designers, engineers, and projects managers, the most significant problems were related to late changes and lack of information/communication. This indicates problems related to requirement capture and the failure to manage the social dimensions of design project delivery.

For project managers, IT solutions played a crucial role, and the main issue for project managers was limited time resources (see **Figure 26**). For building services engineers, the main problems were related to changes and poor coordination, as they are typically involved at the end of the design production line. A small change in the architectural model (e.g., the moving of a wall) can lead to a considerable amount of rework for them; they must also be able to fit their ducts and pipes into tight spaces between floor slabs and ceilings. These results were confirmed during the group discussion, and designers added that limited time to analyze, plan, and also do the work is a major issue.

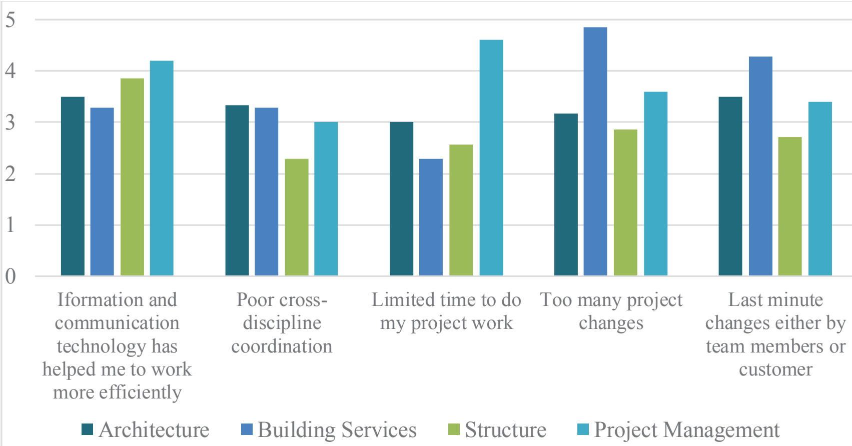


Figure 26. Summary of the survey results by discipline: architecture, structural engineering, building services, and project management.

ERP Database Analysis

The first aspect analyzed was the difference between planned hours of project work and actual hours of project work. According to the data, 50,795 hours of design work were planned, while 50,051 hours were reported. This is excluding sub-contracting hours, for which data was unavailable. Thus, in relative numbers, the overall difference was -1%, meaning that a little less time was spent on work than planned. However, the problem was not in total hours, but in the difference between planned and actual hours spent at the single project level. The average difference between the planned time and actual time for each project category, the figure was 32% for office buildings, 23% for residential buildings, 38% for infrastructure facilities, -6% for commercial facilities, -10% for industrial and warehouse buildings, -9% for industrial and office buildings, and 10% for public buildings. The variance for the difference between planned and actual was 33%. Thus, although overall the projects could be considered successful, at the single project level, there was typically a significant deviation of the actual time spent from the time planned. This means that there was a lot of variation in the difference between time planned and the actual time spent on projects, and the success of any individual project was uncertain.

The average total percentage of design time spent across all 28 projects on each project stage in three different disciplines was calculated. A lot of time was spent on the DD (design development) stage (37.3%) and the CD (construction documentation) stage (51.1%). A relatively small amount of time was spent on the SD (schematic design) stage (2.9%) and the PD (preliminary design) stage (9.2%), where most critical decisions are typically made. Moreover, in these early stages, structural engineering and building services engineering were involved only minimally. However, not all projects had all four stages. For comparison, if only the 12 projects that had at least SD, PD and DD stages were included, the average total percentage of time spent on each of these stages was 6%, 17%, and 77%, respectively. Thus, a lot of time was spent on producing drawings, but not, for example, on working through alternatives to be able to deliver the best value to the client.

Figure 27 illustrates the total work time expenditure relative to project duration. The same 12 projects (out of 28) with the SD, PD, and DD stages were analyzed. When calculating the distribution, all project durations were normalized (to a scale of 1 to 100, where 1 unit = 5), and the curve was produced using a fourth-order polynomial. Projects were divided into two categories, profitable (blue lines) and unprofitable (gray lines). The average contract deadline was determined by adding up all the normalized planned durations of projects expressed in the given units and dividing this sum by the total number of projects. For example, if one project ended four units in, the second nine units in, and the third six units in, then the average would be 6.33 (calculated as (4+9+6)/3).

Figure 27 shows that projects with a resource peak that occurred around the middle of the contract duration were more likely to be profitable. The unprofitable ones had a significantly flatter resource curve throughout the entire life of the project. All projects also had very long tails, which represent time spent on changes, design fixes, and meetings. Overly long tails tend to make projects unprofitable, as clients do not have a contractual obligation to cover the cost of the extra time and resources spent.

To better understand the reasons for these tails, the projects were compared in terms of the time spent on design fixes, changes, and meetings before and after the contract deadline. In the case of profitable projects, 0% was spent on design fixes before the contract deadline and 0.7% after; 2.7% was spent on changes before and 1.6% after; and 7.5% was spent on meetings before and 2.3% after. In the case of unprofitable projects, 3.7% was spent on design fixes before and 2.0% after; 1.0% was spent on changes before and 0.7% after; and 4.5% was spent on meetings before and 1.6% after. The biggest difference seems to be in the amount of time spent on fixes. The projects with more design fixes throughout the entire life of the project tended to be less profitable. This illustrates the importance of assuring quality in the design process from the beginning. Therefore, the conclusion to draw from **Figure 27** is that more focus should be placed on doing the right things earlier in the project to prevent loss-causing tails.

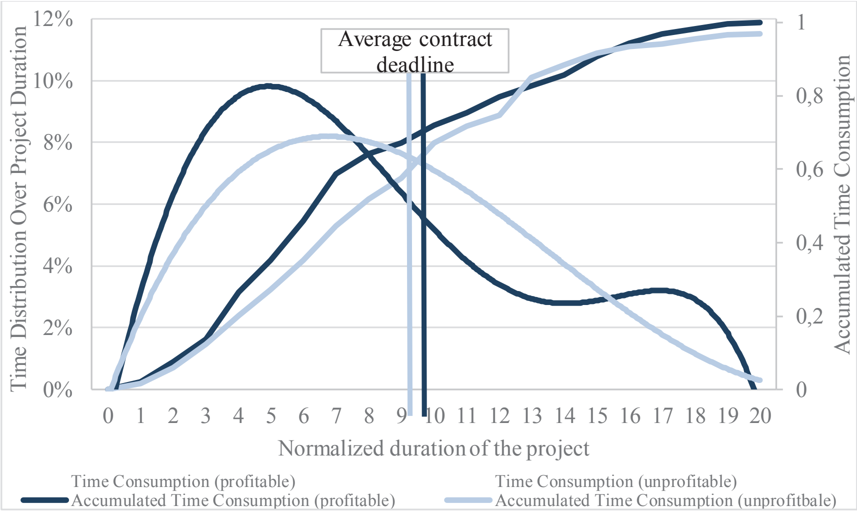


Figure 27. The average work time expenditure over the lifetime of 12 design projects on the left axis and accumulated time expenditure on the right axis. (profitable: blue lines; unprofitable: gray lines)

Figure 28 shows the time distribution over 14 different types of activities across all 28 projects according to discipline. As the data shows, little time was spent on activities such as monitoring and supervising work within the discipline. This could explain the weak oversight (not just the inspection of quality, but also the process of ensuring that the right things are done right the first time) of projects, design problems, and errors leading to fixes. Thus, the lack of design production oversight might be considered one potential cause of project failure.

Based on the internal activity classification system used by the company and assuming that design work is value adding and that everything else is either non-value adding or other (miscellaneous activities not directly related to design or management but still connected with the project), designers and projects managers spend on average 52% of their project-related time on design activities, 39% on non-value adding activities, and 9% on everything else. However, this 52% is a black box, as it is not known precisely on what designers and projects managers spent this time. It was for this reason that the development stage of a single project was observed over the course of eight weeks.

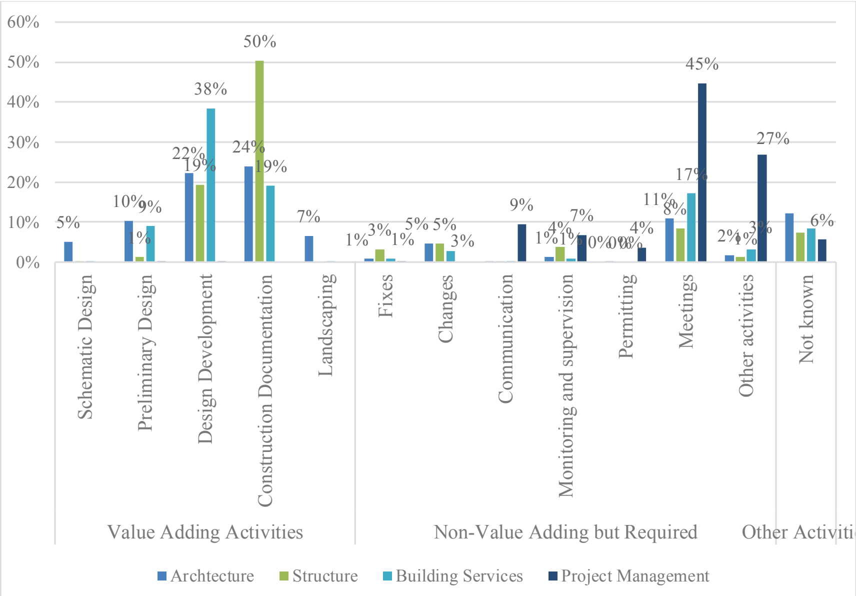


Figure 28. Average activity time distribution by discipline across 28 projects.

Observations of Design Development Stage and Communication Strategies
Over the course of eight weeks, the planned work, progress, and problems discussed during the stand-up meetings were used as input for both the recording of events and observations. The 154 events recorded over the eight week period were divided into three categories (activities 57%, exchange of information 20%, and problem-solving 23%). The exchange of information and problem-solving by discipline (e.g., for architecture, exchange of information 3% and problem-solving 9%) include intra-disciplinary communication events. Out of 154 events, 20 were interdisciplinary events: 1 design activity out of a total of 89 (ca 1%); 9 exchanges of information out of a total of 31 (ca 29%); and 10 problem-solving events out of a total of 35 (29%).

Only one event out of all 89 events was recorded as a collaborative design activity. This occurred when the architect and building services engineer discussed (before the actual designing of the ceilings) what the elevation of the ceilings from the floor should be to provide adequate space for the building services above it. This shows that even when designers and engineers were co-located, they worked together only as the need arose to exchange information or solve a problem. Despite co-location, the design process was still fragmented and driven by partial designs; that is, designs were initially prepared from the perspective of individual designers and coordinated only retrospectively. This lack of collaboration on design activities could be viewed as a significant cause of the need for the late fixes and changes discussed in the previous sub-section.

A total of 89 design activities were recorded, out of which 58% were design and engineering activities (calculations, drawings, specifications, and model coordination), 28% changes, 6% waiting (that means designers had to stop working on an activity and do something else because they were waiting for inputs), 5% control activities, and 3% other activities. Only 58% of the 89 activities among the 154 events recorded could be considered directly value-adding; the rest were non-value adding. Thus, one could argue that only about 30% of the work directly added value.

Next, problems were analyzed to understand their origin. A total of 35 problems were recorded during observations, of which 9% were architectural, 20% structural, 43% building services related, and 29% interdisciplinary. The problems within disciplines were due to lack of information, changing requirements that rendered the solutions that had already been developed useless, conflicting needs and legislative requirements, faulty input information, and poor coordination between disciplines. For example, a client did not want to have a separate toilet for people working in the kitchen, though this was required by current legislation. In another case, changing equipment technology required the development of new building services solutions. A large proportion of the problems (26%) were related to the usage of ICT systems. Either something could not be modelled, or no one knew how to use the application for a specific design task.

Finally, communication and information exchange practices were observed. A total of 33 communication events were recorded. These were divided into five categories: 29% was interdisciplinary communication and consulting on solutions; 26% interdisciplinary coordination; 23% software training; 16% interdisciplinary coordination; and 6% related to drafting conventions. When design team members communicated with each other, in almost every case some tool or object was used as a reference point for communication. Out of 31 communication events, in 55% of the cases, a computer drafting or modelling application was used. In 21% of the cases, designers sketched on either drawings (mostly when discussing changes) or blank paper (mostly for drafting structural connections). In 18% of the cases, designers did not use any specific tool, but communication was verbal. In 6% of the cases, something else was used (e.g., Excel or the project documentation server).

Additionally, the communication practices of two related projects based on an exchange of email were analyzed (with the assistance of a master's student). Though the two projects, which involved the same client and same delivery team, were relatively small in scale, a total of about three thousand emails were exchanged. The key findings are briefly summarized here (for a more detailed analysis (see (Pakats 2017)).

In the case of one project, the project manager received 40% of the email sent by the client and sent 49% of the email sent to the client; in the case of the other project, the figures were 37% and 44%, respectively. This was direct correspondence. Thus, the project manager spent a significant amount of time on managing and sharing information. These communication patterns observed in the two projects reflect the command and control based view of practices. Koskela (2000) argued that mainstream command and control project management concepts were based on the transformation view. The basic assumption of the transformation view of project delivery is that the 'master planner' must be aware of everything in a project, as the 'master planner' is responsible for developing centralized plans, which are then pushed on designers. The same assumption is evidenced by the fact that project managers spent almost half of their productive time in meetings giving progress updates and a relatively large amount of time exchanging information via email, phone calls or Skype, intermediating between the different disciplines involved.

An analysis of the email exchanges revealed that there was no clearly defined stage for the specification of owner needs and requirements, and the specification of requirements continued throughout the entire project delivery process. The analysis also showed that the average duration (measured in days) of email exchanges (the entire thread from beginning to end) between the client or client representatives and the delivery team were longer than the average duration of email exchanges between delivery team members, 3.78 and 2.04 days, respectively. It was determined that the long response times of the client or client representatives had a significant impact on project duration and work progress, an effect known as latency (Chachere et al. 2009).

Additional conclusions were drawn from the observations. Co-location improved reaction speed and problem-solving efficiency. On the negative side, the focus was on problem-solving instead of the avoidance of problems, as there was little discussion of alternative solutions. It was observed that the architect, who sat separately from the co-located team in his/her department, did not participate very much in discussions, making it clear that physical distance or separation can play an significant role in the communication process. In this office, the organization of communication was lacking in many respects. The typical meeting focused on progress reports, while email was often used to identify, develop, and analyze design solutions and verify or validate them with team members or clients.

Summary of Problems in Design Organization and Discussion

The results of the survey, ERP database analysis, and observations revealed different problems in design and design management processes. Here, the main problems are briefly summarized and reflected on. According to the survey results, designers and design managers believed that design processes could be improved. Also, respondents believed that they knew why and where things went wrong. The main problems were related to poor coordination, the uncertainty of information flows, late changes, lack of quality, poor communication, and the untimely responses of clients.

Poor coordination refers to the faulty technical alignment of partial designs across different disciplines. This is an issue faced, for example, by building services engineers, who must be able to fit their ducts and pipes into the tight spaces between floor slabs and ceilings. BIM has been instrumental in improving technical coordination and the communication of designs when the designs are based on digital models. Technical coordination should also address the collaborative study and analysis of requirements, the generation of partial solutions, and the combining of partial solutions to form whole design concepts. According to the observations, only one event out of 89 represented a collaborative design activity. Designers tended to work together only when it was necessary to exchange information or solve problems. The design process was driven by partial designs, and coordination was conducted only retrospectively.

The second problem, the uncertainty of information flows, could be attributed primarily to the poor monitoring of design production. Observations made during the ERP database analysis indicated that there was considerable variation not on the level of total hours planned across projects but on the level of individual projects.

For experienced designers and managers, late changes were considered one of the most critical issues. They were especially problematic for building services engineers, who are directly affected by the decisions made by the architect. The problem can most likely be attributed to poor requirements capture and analysis or the failure to study and analyze alternatives. According to the ERP database analysis, most of the work time was spent in the DD and CD phases, while little time was spent in the SD and PD phases. Moreover, structural engineers and building services engineers had little involvement in the up-front stages of design project delivery. The email analysis also revealed that there was no distinct stage for specifying client requirements, and the specification of requirements continued throughout the entire project delivery process. However, the primary task during the SD and PD phases is to study, elaborate on, and analyze the feasibility of the client's requirements and define the principle solutions. Though a project was much more likely to be successful when most of the work time was spent on the early stages, more time was spent instead on producing drawings.

Problems related to the lack of quality had a direct impact on project outcomes. Although this type of problem was heavily dependent on all of the other problems described above, it is also connected with the quality of individual designs. According to the ERP database analysis, projects which required more design error fixes throughout their life were less profitable for the company. The analysis further showed that little time was spent on monitoring and supervising the design work. Quality assurance is a process that needs to be addressed from the beginning of a project; failure to do so will lead to adverse consequences.

The communication practices studied consisted for the most part of email exchanges. In the two projects, which were observed, the project manager mediated the exchange of information via email between different designers and the client. Such practices proved to be very inefficient, as the average response time for the entire thread from the first email to the last was 3.78 days in the case of design team communications with the client and 2.04 days in the case of internal design team communications. The impact of long waiting times for design input information can be demonstrated through a (necessarily) simplified thought experiment. Let us imagine that a project consists of ten one-day tasks that are sequentially dependent. In the absence of delays in information flow, the total duration of the project would, naturally, be ten days. If the average delay in the acquisition of information were one day, total project time would be 19 days, 28 days if the average delay were two days, and so on. Thus, latency has a remarkable impact on the total duration of a design project. It is also noteworthy that according to the ERP database analysis, design managers spent up to 45% of their time in project meetings, which were used as a mechanism for exchanging information between different parties.

The client's lack of timely responses can be interpreted in two ways. On the one hand, delays in responses to a designer's request for information may simply be due to complex processes in the client's organization. On the other hand, delays might also be attributable to the fact that clients are not adequately integrated into the design production process and not informed well ahead of the decisions to be made. For example, the function of pull planning is to inform all members of the design project team of upcoming decisions, weeks, sometimes even months ahead.

What were the key mechanisms at work in the managing of design process? Based on the empirical analysis, the only visible framework for managing design activity and projects was classical project management. This is reflected in the communication and management practices of the design office, while the primary focus was on managing design tasks and resources. The principal tools used in project planning and coordination were the traditional Gantt chart and weekly or bi-weekly meetings. The focus of the weekly or bi-weekly meetings was on the mapping of the deviations between the planned and actuals from week to week without reference to higher level plans (master and phase plans). Also, the fact that about 40% of emails were either sent or directly received by project managers reflects the command and control based view of project management. Furthermore, even when a project team was co-located, designers only worked together if there was a need to exchange after-the-fact information or solve problems. This can be attributed to the fact that the design manager was not co-located to facilitate work in the co-located space.

Though not all of the problems can be attributed to design management practices, poor management led to adverse consequences in three different domains: study and analysis of problem and solution spaces (design task); design production and its monitoring (design process); and collaboration (communication, coordination, and cooperation). According to Koskela et al. (2002), the root cause of these problems in design management is its conceptualization. Koskela et al. (2018) argued that traditional/mainstream management conceptualizations were developed on the basis of erroneous epistemological premises. Similarly, it is also argued here that a poor conceptualization of design management induced many of the problems observed in the design office.

However, any conceptualization of design management depends first on an understanding of its subject matter. A poor conceptualization of design management in fact arises from a poor understanding of the nature of design activity. The development of a better conceptualization of design activity has been the primary focus of this thesis. Hence, the following sections describe the interventions that were designed to eliminate or mitigate the problems established in this section by incorporating the findings of earlier chapters.

6.3.3 Intervention Design, Action Planning, and Implementation

This sub-section develops the design management knowledge base needed for the design of the interventions and action planning. The objective is to briefly describe the lean design management practices underlying design and action planning.

First Iteration: Design, Action Planning, and Implementation

The first iteration was explicitly approached from the perspective of design management. Specifically, it addressed the problems related to poor coordination, uncertainty of information flows, poor communication, the client's untimely responses, and lack of quality.

As a first step, a practical instantiation of the framework depicted in **Table 20** was carried out. The objective was to develop a common understanding of design project management and the related functions of project-based production systems and operations. This was recommended by the author of this thesis, and the content of each section was agreed with the members of the design organization. According to the TFV theory, design production system management has three functions (Koskela 2000): design system design, design system operation, and design system improvement.

The design of a design production system must be approached from the three perspectives of production, namely, value generation, transformation (what needs to be achieved), and flow (how best to achieve it). In 2002, Bertelsen and Koskela (2002) argued that the management of these three aspects at the production system level follows a loop from value management to transformation management to flow management and back to value management. The main design system activities involved are the starting-up of the design project, the establishing of project guidelines for working together, and the establishing of a shared vision for the project.

The operations management of a system is divided into planning, supervising, and correction management activities. These functions are repeatedly applied in different design project phases, i.e., schematic design, preliminary design, design development, and construction documentation in the context of Estonian legislation and standards. Each phase can be further broken down into a sequence of generic design phases, as proposed in the new design model: invention (problem and solution framing), solution generation (concept and embodiment), implementation, development (construction and testing), and delivery (evaluation).

Design system improvement is focused on the gathering of contextual information for improvement of design system design throughout the different stages of project delivery and to the end of the project. Typical activities in this stage include a comparison of the planned and actual and the collection of feedback from the client and designers. The general structure of the design project production system, together with essential production and management functions as well as general activities, are summarized in **Table 20**.

Table 20. The design office's new main process structure.

<table>
<tr><th colspan="2">Design System Design</th><th colspan="5">Design System Operation through Different Stages</th><th colspan="2">Design System Improvement</th></tr>
<tr><td rowspan="6">Contract</td><td>Project Brief and Planning</td><td rowspan="6">Start-Up Meeting</td><td>Plan</td><td>Execute</td><td>Control</td><td rowspan="6">Phase End Meeting</td><td>Phase or Project Finishing</td><td rowspan="6">Project End Meeting</td></tr>
<tr><td rowspan="5">Initial project information, clarification of deliverables, assignment of head designers, required surveys and research, resourcing, project program (scope, cost, time, and quality), team creation, and establishment of common understanding</td><td colspan="3">Invention (problem and solution framing)</td><td rowspan="5">Project summary (time, cost, and quality), bonuses, customer feedback, assessment of partners (trade partners), and lessons learned</td></tr>
<tr><td colspan="3">Solution Generation (concept and embodiment)</td></tr>
<tr><td colspan="3">Implementation</td></tr>
<tr><td colspan="3">Development (construction and testing)</td></tr>
<tr><td colspan="3">Delivery (evaluation)</td></tr>
</table>

The model developed was the basis for understanding the function of management in actual design activities. This model helped to align the logic of the Last Planner System to internal design management processes. The Last Planner System was devised to ensure reliable design process flow by improving communication and establishing a network of commitments among Last Planners. What followed was the implementation of this framework, with the main focus on the collaborative planning of design work.

The author of this thesis supported a design team in its efforts to implement the Last Planner System in a design project in eastern Estonia. The author of this thesis worked together with the project manager, design team, and client first to establish a master schedule, quality plan, communication plan, and financial plan during the project briefing and planning phase. Each design phase began with phase scheduling based on 'pull' principles, to help the design team better manage the sequence of work through the communication of what needs to be done, what they need to do it, and the best way for them to do it. An example of a pull planning meeting outcome for the design development phase is illustrated in **Figure 29**.

Figure 29. An example of phase plan prepared based on the pull technique.

The overall logic for phase planning was as follows:

1. First, the time needed for design review by the customer (two weeks) was subtracted from the phase duration.
2. Another week was subtracted to leave time for the correction of design errors. This was more than actually needed, according to the design team, but it would give them some leeway as the project evolved and the situation changed. This was almost providential, as one designer was ill for a week, and because of the generous time allowance the team still managed to complete the preceding design development phase on time.

3. The entire design phase was divided into two-week design sprints.
4. Each discipline had to clearly define the output of each design sprint by moving backward from the end of the phase.
5. Each discipline had to define its tasks in the delivery of the sprints and identify the inflows it required (decisions, information, research, etc.).
6. Next, the required tasks for all disciplines were defined, e.g., design reviews by the design manager and clash detection after every second design sprint.
7. Finally, a three-hour meeting was held to discuss, specify, and clarify the sequence of work and handoffs and discuss any remaining issues.

Also, during the implementation, an emphasis was placed on 'lookahead' planning, which was connected to the tasks identified in the pull planning. A sticky note structure was used, where at the bottom of the note each design discipline was required to identify anything necessary for them to deliver their work (see **Figure 30**). The 'lookahead' plan was continually managed and tracked by the project manager. Every second week, a client meeting was held to provide the client with an update on progress, plans, and problems that needed to be addressed. After each client meeting, a team meeting was held, and the necessary changes in the pull schedule were made.

<table>
<tr><td>Assignee:</td><td>Duration:</td><td>End Date:</td></tr>
<tr><td colspan="3">Task Name:</td></tr>
<tr><td colspan="3">Prerequisites:</td></tr>
</table>

Figure 30. Pull planning sticky note outline.

The uncertainty of information flows, poor communication, and the issue of untimely responses from the client were addressed by implementing the Last Planner System (specifically, in the phase planning) and bi-weekly client meetings. All designers participating in a phase delivery were required to define their sprints, tasks, and information requirements. Furthermore, input required from the client was determined in the collaborative pull planning meetings. Poor technical coordination was addressed by adding the necessary design coordination tasks and meetings to the phase plans. Similarly, the lack of quality was addressed by including compulsory design reviews in phase plans.

Second Iteration: Design, Action Planning, and Implementation

In the second iteration, the focus was on the design process description, particularly on the stages, phases, and activities of each design and engineering discipline and interactions between them, including also managerial activities. Notably, problems related to the uncertainty of information flows, late changes, lack of quality, and poor communication were addressed. This focus was selected based on the initial feedback from the designers and design managers.

The high-level process model shown in **Figure 31** was the result of meetings held to establish the company's primary business process. It is normative in the sense that it corresponds to the ideal design project situation. Stages related to sales were excluded from the model. Although the names of the phases were selected in accordance with the Estonian Building Design Standard (ECS 2012), the content of the stages corresponds to that of the stages in the new model developed in Chapter 5: schematic design corresponding to requirements capture; preliminary design to concept design; design development to embodiment; and construction documentation to implementation stage.

The project begins with a contract milestone meeting, and every phase begins and ends with its own milestone meeting, which involves all stakeholders in the design project. The aim is to focus first on the rhetorical perspective, then move on to the method of analysis perspective and eventually back to the rhetorical perspective. At the beginning of the project, the rhetorical approach is concerned with the establishment of expected value propositions and a commitment to phase objectives, while at the end, it is concerned with an evaluation of design solutions against value propositions. In other words, two meetings are required: the design briefing meeting and the client review meeting, and a standardized structure is proposed (objectives, participants, typical agenda and expected outputs).

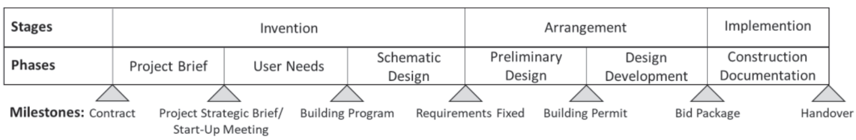


Figure 31. The ‘high-level’ (first level) process model.

The flow from one milestone to another requires completion of activities and deliverables that form a baseline for the subsequent phase. Based on the high-level process framework, second level process models were developed. Specifically, two types of standardized second level process models were developed, one for the project briefing and the other for the remaining design phases.

The detailed model for the project briefing phase is shown in Appendix V. The managerial and design activities in this phase are mostly concerned with strategic aspects of the project, such as assessment of the need for a technology project, surveys, research, resources, and trade partners. Activities also include the establishment of a project program and arriving at a shared understanding of project objectives, working methods, collaboration practices, and expected behaviors through team and start-up meetings.

The standardized process model for all phases except the user study and schematic design phases is presented in Appendix V. The user study and schematic design phases were omitted by a decision of the quality team. The justification was that this company had had only a few projects in the past where they were also responsible for these phases. Most of the company’s projects started with the preliminary design phase. When developing the standardized phase model, the assumption was made that each phase should follow a similar process. Of course, in reality, the processes are never the same, and it is the skill and experience of project managers, lead architects, and engineers that determines which activities are necessary or not in a given phase.

The phase cycle of planning, execution, and control consists of two sub-cycles of planning, execution, and control: weekly or bi-weekly and daily cycles as shown in **Figure 32**. The weekly or bi-weekly cycles describe the flow from planning meetings with client and team to work execution and control and then to the coordination of work-in-progress through model coordination and resolution and finally back to team planning sessions. The daily cycle is followed in the work carried out by individual designers.

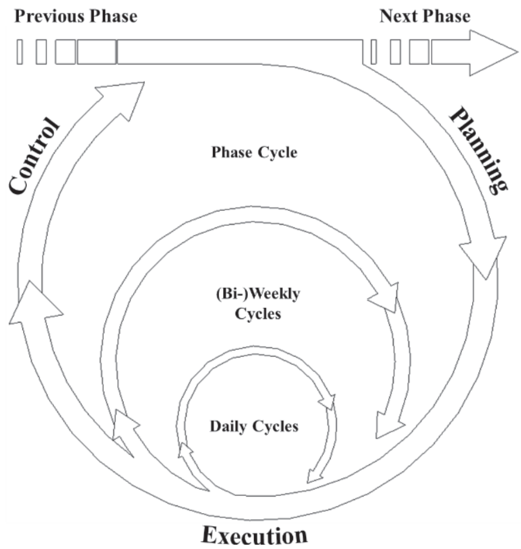
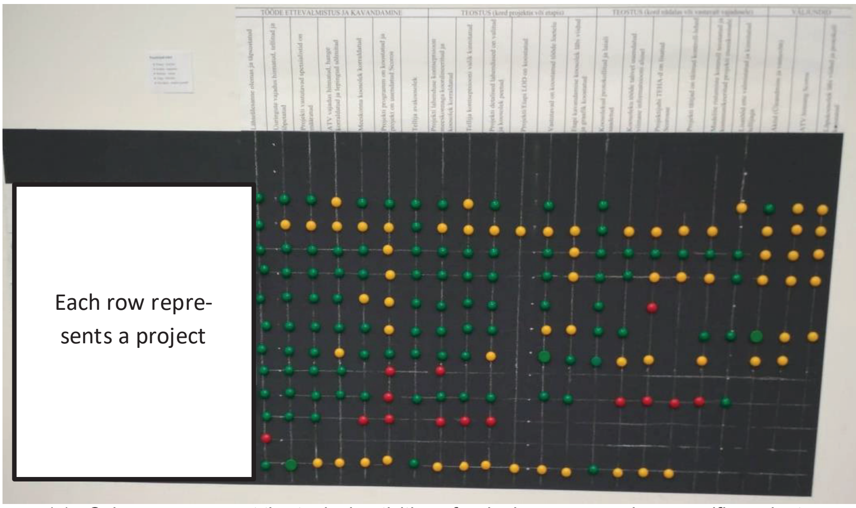


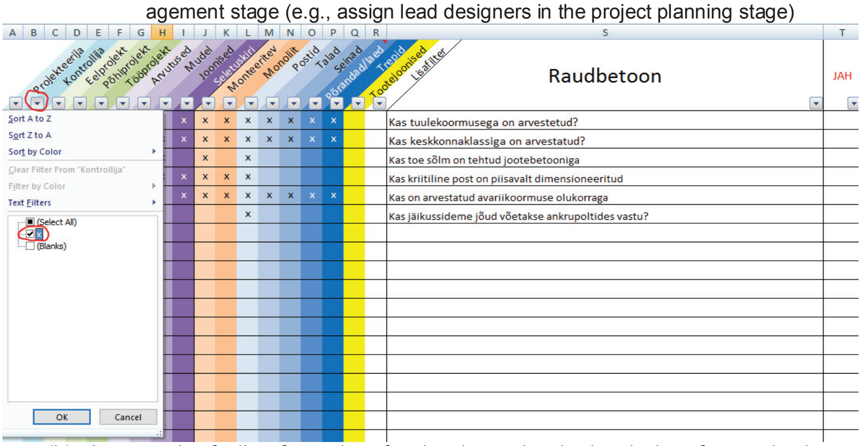
Figure 32. The three nested cycles of operations management.

To implement the model in the design office, it was introduced to the whole organization department-wise by participants in the model development meeting; i.e., the head of structural engineering introduced the model to the structural engineering department, the head of architecture to the architectural department, etc.

The proposed model became the basis for the development of further improvements, including but not limited to: checklists, meeting templates and structures, a new classification system for design activities, a BIM execution plan, and visual control tools. From example, **Figure 33** provides an example of two different checklists: (a) a visual checklist of critical activities for design managers, (b) a checklist for designers to be used when planning and reviewing designs.



(a) Columns represent the typical activities of a design manager in a specific project management stage (e.g., assign lead designers in the project planning stage)



(b) An example of a list of questions for planning and reviewing designs for cast-in-situ reinforced columns).

Figure 33. (a) A visual checklist of critical activities for design managers and (b) a checklist for designers to be used when planning and reviewing designs.

Most notably, to make the new process-oriented management of the projects successful, the organizational structure was changed from departments to disciplines. The typical tasks of the heads of the departments were shared by the CEO, project managers, lead designers and engineers. Also, the bonus system was changed from department-based to project-based, where bonuses were tied to a project's overall success, thus motivating different disciplines to work together.

A procedure for implementing the new primary process was also developed. Every Wednesday the CEO of the company had a stand-up meeting with all projects managers to monitor whether what was outlined in the process model was being followed and whether the developed tools were being used. When deviations were identified, their reasons were documented to be used as input for future improvements.

In summary, in the second iteration, many essential interventions were introduced. Most importantly, problems related to poor coordination, uncertainty of information flows, lack of quality, poor communication, and a client's untimely responses were addressed by introducing the process models, checklists, meeting templates and structures, and visual controls. A new organizational structure and bonus system were introduced to align the interests of different participants in the organization.

6.3.4 Evaluation of Interventions

The impact of new interventions was continuously evaluated throughout the two iterations. For example, a few months after the first iteration, written interview questions were sent to the persons who participated in the development of new design management practices. The interview questions, focused on what had changed by comparing processes and problems before and after the first iteration. Four who responded agreed that a common understanding of leading design management tasks and processes had improved. However, respondents also stated that the content of phases, that is, design and managerial activities and their interdependencies were not explicit. This limitation was a starting point for the second iteration, which would serve to explicate design and managerial processes.

After the second iteration, a two-step evaluation was conducted, consisting of a focus group interview and an ERP database analysis. Ten people from the design organization took part in the focus group interview. The task of the groups was to assess the impact of the interventions based on the statements of the problems/issues identified in the first survey (see Appendix IV). For a more objective evaluation, the database analysis was conducted to compare the performance of projects before and after the interventions.

Focus Group Interview Results

Table 21 summarizes the primary outcomes of the focus group interview. As the results indicate, focus group participants experienced improvement in all categories of problems. In the case of statement 7, one group answered 'neutral', given that no member of that group had yet participated in the pull-based planning sessions.

All groups seemed to agree that planning, execution, and control systems were more coherent and transparent. The improved design management system led to better change management, resource management, coordination, and communication practices. However, one group did point out that the changes made sometimes caused new interdependencies, and these were not adequately communicated. Thus, change management and design coordination issues need to be addressed in future interventions.

Table 21. Summary of focus group interview answers.

Statements	Group 1	Group 2	Group 3	Summary of justifications
1. Team members are not available when needed	Improved	Improved	Improved	More coherent planning, execution, and control systems have reduced this problem
2. Team members have poor qualification and experience	Improved	Improved	Improved	Over the last two years, the effort was made to improve the overall average competences of people hired in the company either by training or discharging unqualified employees
3. We often postpone problems which should have been dealt with immediately	Improved	Improved	Improved	More transparent planning, execution, and monitoring of design work has reduced the possibility of postponing problems
4. I would do my projects better but lack sufficient knowledge	Improved	Improved	Improved	Over the last two years, the effort was made to improve the overall average competences of people hired in the company either by training or discharging unqualified employees
5. Limited time to do my project work	Improved	Improved	Improved	Due to improved design management, the time given to designers and engineers has become more realistic and reliable. Also, the management of client changes has improved, allowing us to ask for extra time. One significant difference is that we do not start a project immediately without having all the necessary prerequisites for doing the work; this saves us doing rework.
6. Clients do not resolve problems in a timely manner	Improved	Improved	Improved	From our end, communication with customers regarding their responsibilities and expected behaviors has improved. However, in the end, success depends on the specific client and their willingness to play along with the rules of the project.
7. It is often uncertain when I will get necessary input from other designers	Improved	Improved	Neutral	Phase pull planning has improved workflow and the reliability of plans.
8. Cross-disciplinary coordination is poor	Improved	Improved	Improved	New design and design management processes have improved the coordination between designers who are directly involved. However, changes sometimes cause new interdependencies which are not adequately communicated.

Groups were also asked four generic questions to facilitate discussions. Below, the answers to these questions are briefly described, and examples of answers are given to illustrate the different views.

First question: Please describe the difference between the overall understanding of design processes and design management practices in the design office before and after the interventions. Three examples are given to illustrate the responses:

- Project Manager: “I would like to give an example based on my early experiences as a project manager. When I started in this company as a pro-

ject manager I was worried about summer vacation, and I asked a structural engineer "what is the deadline and when should we start?" He answered, "it is just the start of the project, and in the first two weeks typically nothing will happen!" Initially, I thought this was how things are, but this mindset has changed over the last two years."
- Head architect: "There have always been 'some' kind of processes, but it has only been over the last two years that processes have been explicitly addressed."
- Board member: "Overall awareness of what is good practice and process has increased within the company."

Thus, based on these answers, it appears that the overall mindset regarding design management and processes has changed. The explicit description of processes, including the responsibilities and deliverables of different project participants, has helped to develop a better overall awareness within the company.

Second question: Please describe the difference between the overall understanding of design processes and design management practices in the design office before and after the interventions. For the second question, four examples are given:
- CEO: "Overall, the quality of the workplace has improved for employees because there is less uncertainty in the process and therefore fewer people being worried about how the project will go."
- Lead Structural Engineer: "It seems that clients are more satisfied, and people within the organization also seem to be more satisfied with their work."
- Project Manager: "Transparency across different disciplines has increased. The lack of transparency negatively affected employee psychology. I mean, before no one knew the overall progress of a project, and this made employees work in the dark."
- Head Architect: "On the other hand, the new system has made the weak links within our project teams more visible."

Several aspects become evident in these responses. First, the psychological conditions of working in the company have improved. Secondly, customers seem to be more satisfied with the course and outcomes of the design process. Thirdly, and this can be viewed either positively or negatively, the weak links within the project teams have become more apparent. To the author's knowledge, over the course of this research project, a few employees were replaced by the company.

Third question: What are the necessary next steps to be taken by the company to sustain improvement in the short term? For the third question, two examples are given:
- Board Member: "We need to continue working and maintain the discipline of working according to the agreed processes. We also need to work as a team and remind each other, if and when necessary, what each other's responsibilities are."
- Project Manager: "We need to keep comparing the process model against actual processes, and whenever there is a deviation, the reasons

need to be analyzed. Not only because there are problems, but maybe there are better ways of doing things!"

Here, also, several important aspects are brought out. Namely, the board member emphasized the need to work as one team and support each other whenever necessary, i.e., not by doing someone else's work, but, if necessary, reminding other team members of their responsibilities and tasks, as established by the new process models. The project manager also rightly emphasized the importance of continuous improvement.

Fourth question: What are the necessary next steps to be taken by the company to sustain improvement in the long term? In this case, only the board member answered:

- Board Member: "Often, when something becomes a norm in everyday work, we tend not to notice these things! This is especially the case with 'what is good in the company' and therefore, we do not praise that. However, we should be proud of our achievements and also let others outside the company know."

The answer to this last question is crucial. Within design companies, one should focus not only on the things that are bad but also on the things that are good. This helps keep the work experience positive and sustain motivation to strive forward.

Thus, from these answers and examples, it appears that the interventions have had a positive impact on people working in the company. In addition to all of the constructs, methods, and tools that were introduced in the company, the most critical difference was in the change of the mindset of people working in the company. This is apparent in the responses given by employees of the design company during the focus group interview. For example, a project manager shared his experience of how the mindset regarding project schedules had changed.

Database Analysis Results

To provide an objective evaluation of the impact of changes in the organization, an additional macro-analysis was conducted of projects that started after the introduction of new interventions and were completed before the end of this research project. This made it possible to compare these projects to the ones analyzed in sub-section 6.3.2.

Out of the 28 projects that were completed before the first iteration of new interventions, only half were profitable. However, out of the ten projects selected for this analysis, only two projects did not make a profit. **Figure 34** (a) and **Figure 34** (b) summarize the overall performance level of design project delivery. The black dots represent old projects selected in the ERP database analysis sub-section 6.3.2. The gray dots represent projects that were started and completed after and during the first and second iteration.

The horizontal axis on both **Figure 34** (a) and **Figure 34** (b) represent the design organization's ability to meet the initial resource commitments (number of hours of design work). The gray dots on the horizontal axis appear to be closer to zero, meaning that time-wise these projects deviated less from the initial plan. Pre-intervention projects, however, tended to spend a lot more design hours to complete work than was initially planned. In one case, design hours required to complete a project exceeded planned hours by more than 200%.

The position of dots on the vertical axis in **Figure 34** (a) represents the percentage difference between the original bid price and the end cost for the client. The figure shows that in the case of pre-intervention projects (black dots), in many instances the final cost for the customer was higher (above the horizontal axis) than initially planned. On the other hand, in the case of the new projects (gray dots), three projects were remarkably more costly for clients. The difference can be atttributed to improvements in change management. Namely, design management became more capable of tracking customer changes and negotiating extra fees.

The vertical axis in **Figure 34** (b) represents the percentage difference between actual customer cost and actual cost for the design company. When the percentage difference was above the horizontal axis, the company lost money. While just two of the new projects (gray dots) lost money, most of the old projects (black dots) lost money.

As a high-level indication of impact, the design office, which failed to make a profit in 2015, had a profit margin of 5.5% in 2016 and 20% in 2017. Thus, profits had improved dramatically, and 2017 was the most profitable year in the history of the design company.

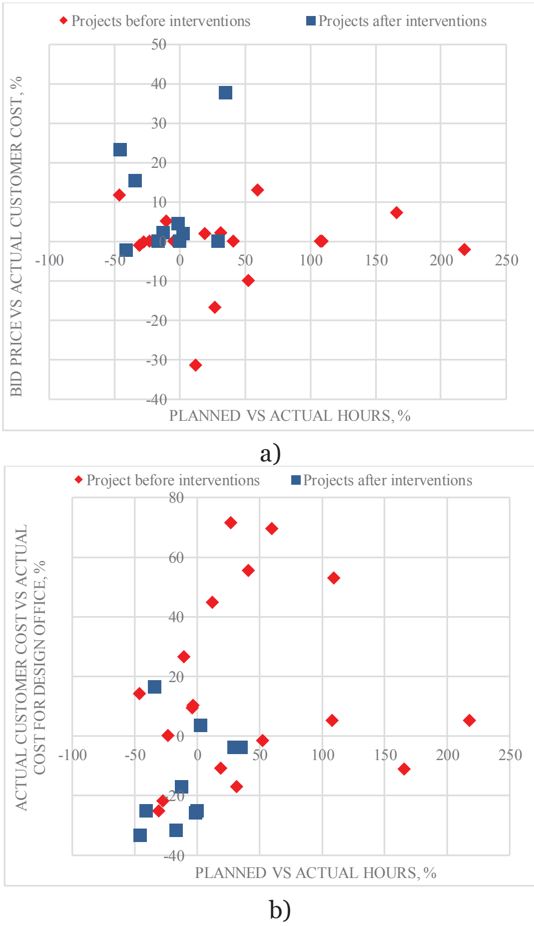


Figure 34. Two-dimensional comparison of project performance and variation before and after the inventions: a) the vertical axis represents the relative difference between initial resource need (budget) and actual consumption; b) the vertical axis represents the relative difference between actual cost for the customer and actual cost for the design office.

6.3.5 Discussion and Summary

Building design and design management are often beset with certain well-known problems, and management practices in this case study were no exception. Through surveys, a database analysis and observations, many problems were identified, and this led to the conclusion that it was a poor design conceptualization that led to a poor conceptualization of design management. The focus of design project management was on the management of tasks and resources through formal methods and mechanisms, such as Gantt charts and (bi-)weekly meetings. Furthermore, communication patterns followed the principles of the command and control view of design management. However, it is not possible to manage design without better understanding its nature.

The new model developed in Chapter 5 was used as a baseline for the development of interventions and instances of design artefacts with the aim of improving practices. In the first iteration, a general design management framework was established. The objective was to address problems related to poor coordination, the uncertainty of information flows, poor communication, a client's untimely responses, and lack of quality. Based on the new design management framework and design model, several interventions were introduced: the Last Planner System and bi-weekly customer meetings to address the uncertainty of information flows, poor communication, and a client's untimely responses; compulsory design coordination tasks and review meetings for phase plans to address poor technical coordination and deficiencies in quality.

In the second iteration, a collective description for two levels of processes was developed, and they were implemented in new organizational and bonus structures. The new organizational structure and bonus systems were introduced to align the interests of different participants in the organization. The objective of the collective description of design processes was to improve overall awareness, among all members of the design office, of typical design stages, phases, milestones, activities, and deliverables. This became the basis for introducing many other interventions. Process models, checklists, meeting templates and structures, and visual controls were thus introduced to address problems related to poor coordination, the uncertainty of information flows, the deficiencies in quality, poor communication, and a client's untimely responses.

In this case study, although the impact of new interventions was continuously evaluated throughout the two iterations, the principal evaluation was carried out at the end of the development project. The two-step evaluation consisted of a focus group interview and macro-analysis of projects. In the focus group interview, ten people from the design organization were asked to assess the impact of the interventions based on the statements of the problems/issues identified in the first survey (see sub-section 6.3.2). The macro-analysis, based on data from the ERP database, was carried out to evaluate the performance of projects before and after the interventions.

In the focus group interview, participants, with the exception of one group, which answered 'neutral' to statement 7 in **Table 21**, stated that they had experienced improvement in all categories of problems. The main impact of the interventions, according to the participants, was that the planning, execution, and control of design process had improved, and this also led to better change management, resource management, and coordination and communication practices. Planned project durations had become more realistic and reliable. Coordination had improved, and people in the company understood the importance of prerequisites, as projects were no longer started if significant inputs were missing. Communication of customer responsibilities and expected behaviors had also improved. At the same time, participants indicated that change management needed to be addressed in future interventions. Thus, based on these answers and examples, it appears that people working in the company felt that the interventions had had a positive impact.

In the second step, the macro-analysis of projects, significant improvements were identified in the projects completed after the interventions. The analysis indicated that time-wise these projects had deviated less from the initial plan. This agrees with the statements of focus group interview participants. While they pinpointed the importance of further improving change management, the macro-analysis demonstrated that some improvements had already been achieved. Moreover, the company seemed to have proportionally much fewer projects that did not make a profit. This is also reflected in the 20% profit margin in 2017, when it was just 5.5% in 2016, and there was no profit at all in 2015.

In summary, although it is difficult to pinpoint precise cause and effect relations regarding how interventions impacted design and design management and to what degree, the results show qualitative and quantitative improvements in design project delivery. In addition to all the constructs, methods, and tools that were introduced in the company, perhaps the most critical difference lay in the change in mindset of the people working in the company. This is apparent in the responses given by the employees of the design company during the focus group interview: members of the design company had started to believe that things in the company could be improved. Thus, the participatory approach to designing, implementing, and evaluating interventions had helped not only to develop better ways of doing work but also to improve the company's capacity to learn and continuously evolve.

6.4 Discussion and Implications

In this chapter, the objective was to evaluate the utility of the new design model. It was assumed that the instantiations and implementation of the new design model would bring about practical benefits in three case studies, more specifically, in the early stages of the design of a warehouse building, the conceptual design of energy and cost efficient buildings, and design management in a building design company.

First Case Study on the Early Stages of Design

In the first case study, the methodological aspects of the early stages of design were investigated. The study focused on activities and outcomes involved in the development of the early stage concept for the warehouse. The new model supported the development of an understanding of the scope and activities of the different design stages: (1) the given situation and project start-up, (2) a situation analysis and goal formulation, (3) establishment of way of use (use plan) and product characteristics, (4) and solution framing.

The first stage was a managerial stage; the latter three were design specific stages. In the first stage, the design project team was formed, and the overall strategy of design staging for the development of the project was defined. In the second stage, although causal aspects were considered, the main focus was on interpretation and problem formulation with a view to the development of arguments for clients and users that would also lead to new discoveries. The third and fourth stages were concerned with solution framing, which was carried out through several iterations of individual and collective work. In the last two stages, different kinds of media, e.g., building information models, were used to communicate, test, and collectively evaluate the designs.

More general implications could be inferred. In the early stages of design, iterations are an inevitable part of the design process, not only for the testing of ideas, but also for the development of a collective understanding of the design task, problems, and possible solutions. During this process, a clear articulation of the project value structure regarding targets and constraints is needed to facilitate communication and the iterative design process. Furthermore, the architect can strategically use constraints by adding or removing them at will since the design task in the early stages is typically (though not always) underconstrained. This means that there are many possible solutions, though, to be sure, having either too many options or too few to consider is not practically useful. Finally, the design process is a collective effort. Therefore, it is crucial to manage and organize design processes. In this project, the absence of design management led to a delay of three months.

In summary, design in the early stages is primarily concerned with interpretation, designing for humans with humans. Nevertheless, designing also involves the use of functions, methods and tools throughout the entire process to facilitate collective work. For example, in this project, BIM, energy simulations, cost calculations, and structural analyses were used to study the feasibility of the design solutions. Thus, though the design process may seem linear on the macro-level, on a micro-level, the process involves a cycle of conception and deliberation in the analysis, and mental/symbolic/external actions and perception/sensory experience in the synthesis. These are the fundamental human activities underlying the process, and this is what allows the design to progress.

Second Case Study on the Robust Energy and Cost Efficient Design of Buildings

In the second case study, the new model was used to investigate the methodological questions involved in the conceptual design of energy and cost efficient buildings. The study focused mainly on the activities of the conceptual design process and their relationships. The new design model made it possible to understand the scope and steps of three methods, the integral morphological C-K design method, the Taguchi robust engineering method, and BIM, and align the steps of these different methods to the process stages, the causal structure of the design process, and mental and practical design activities. The proposed framework for aligning the methods based on the new design model made it possible to design more energy efficient buildings at a reduced level of initial investment and with less sensitivity to noise factors. The results achieved were significantly better than the figures for the constructed facility and those reported in the original study by Pikas et al. (2015). This fact is especially significant, as the gap between the actual and modelled energy consumption of buildings is often a significant problem. The robustness analysis was made possible by the use of factorial methods in the sensitivity analysis.

A few general conclusions were drawn. First, conceptual design is essential when defining design criteria (ideal functions) that are relevant to the building owner. The design of energy and cost efficient buildings is a multidisciplinary task, as the generation, judgment, evaluation, and selection of design alternatives requires a consideration all relevant perspectives. Furthermore, the evaluation and selection of design concepts should not be carried out without an understanding of the performance of building designs; and this requires a study of the robustness of different design concepts. Noise factors in the design process are of critical importance and should not be neglected, as every project is a unique one-of-a-kind prototype. The final selection of a design concept requires collective evaluation. BIM should be used to facilitate communication among project team members.

There are two other, more general implications. First, although there is still a need for the collaborative interpretation of designs, the conceptual design of energy and cost efficient buildings is focused on the technical aspects of building design – causal considerations of the design process. Thus, the conceptual design of energy and cost efficient buildings mainly takes the perspective of the method of analysis. Secondly, companies developing applications for dynamic energy simulations should consider adding functionality that makes it possible to assess the impact of variations in noise factors on building performance. Designers and energy specialists need tools to design more robust buildings, buildings less subject to noise from different sources.

Third Case Study on the Design Management

In the third case study, the new design model was implemented in a design management context. Although, in general, problems in building design and design management are well known, surveys, a database analysis, and observations helped to identify several problems arising across specific design projects. It was concluded that poor conceptualization of design management was the reason for many problems in the design company. Furthermore, it was also argued that poor conceptualization of design activity caused poor design management. Without an understanding of the stages, the iterations required, the causal structure of transformations, and the necessary mental and practical activities of designers, design management cannot be improved, as design management is the management of design activity. The new design model together with the design management baseline formed the foundation for the introduction of interventions in the design company. The longitudinal case study progressed through two iterations, where the main focus advanced from development of a general design management framework to the implementation of design processes at different levels of detail.

In the first iteration, the objective was to address the problems related to poor coordination, the uncertainty of information flows, poor communication, a client's untimely responses, and the deficiencies in quality. **Table 20** defined design project management functions (design system design, design system operation, and design system improvement) and typical activities together with general milestone events (the contract milestone, the start-up meeting, phase end meetings, and the project end meeting) and design operations management functions (plan, execute and control). Additionally, the general structure of design phases based on the new model were described: invention (problem and solution framing), solution generation (concept and embodiment), implementation, development (construction and testing), and delivery (evaluation). The design management framework guided the introduction of several interventions: the Last Planner System and bi-weekly customer meetings; necessary design coordination tasks and review meetings.

The second iteration addressed similar problems. However, the focus was mainly on the collective description of processes. These were implemented in new organizational and bonus structures, which aligned the interests of different perspectives. In the past, every department was a separate entity with its own budget and bonus system. Now bonuses were project-based. Several interventions were also carried out in the second iteration: in addition to the process models, checklists, meeting templates and structures, and visual controls were also introduced.

The main evaluation of impact in the second case study was carried out at the end of the development project. Outcomes were evaluated through a focus group interview and a macro-analysis of projects. The results of the focus group interview made it evident that improvements in almost all categories of problems had been experienced. Overall, the improvement of design management was evidenced by better planning, execution, control, change management, resource management, coordination, and communication of and in design practices. Regarding future interventions, participants indicated that change management still needed improvement.

The macro-analysis of projects was subsequently carried out. According to the macro-analysis, projects now deviated less from the initial plan, there were proportionally fewer projects where no profit was made, and although participants in the focus group interview indicated problems with change management, the macro-analysis demonstrated that some improvements had already been achieved. In short, considerable qualitative and quantitative improvements had been witnessed in the company after the interventions. Most importantly, the interventions changed the general awareness of employees of possibilities for improving design and design management practices.

In the third case study, there were additional general implications. First, the involvement of design managers and designers in the action research not only made it possible to develop new interventions but was essential for getting them to buy into the new approach. Secondly, design managers and designers need a common framework for thinking about design management and design activities in order to facilitate dialogue. In this study, the new design model together with design management formed a baseline for participative action research. This also opened action research participants to seeing possibilities for the introduction of practical interventions, such as process models, checklists, meeting templates and structures, and visual controls. Thirdly, as the focus group interview results indicate, the process of improving design processes and the management of these processes is not a one-time event, but must be a continuous pursuit. The most practical way to sustain improvements is to integrate continuous improvement processes into the company's routine practices.

Across Case Studies

Together, the three case studies demonstrated that significant quantitative and qualitative improvements could be achieved by introducing the new design model together with complementary instantiations, such as a design management framework. In the first case study, the new design model as a common framework for the design team made it possible to collectively develop an innovative warehouse concept. In the second case study, the practices introduced based on the new model made it possible to design more energy efficient buildings at a reduced level of initial investment and with less sensitivity to noise factors in the conceptual design stage. In the third case study, design and design management practices were improved, resulting in a more consistent overall delivery of design projects. In the next chapter, the general fulfillment of success criteria is evaluated.

However, as a general note, the evaluation of utility through three case studies cannot be conclusive. Further studies are required to increase the representativeness of the results in a broader context. Also, the additional elements implemented, such as the Taguchi method and visual controls, etc., could also be the reason for the good results, rather than the underlying model.

6.5 Chapter Summary

The objective in this chapter was to evaluate the utility of the new design model through three case studies and answer the question of whether the new model helps to improve design and design management practices.

In the first case study, the new model facilitated the development of a common understanding of the design process, and this was necessary for the development of a shared vision of the design task in the early stages of design. Specifically, the study focused on the investigation of the situated subject and object-oriented activities, and this resulted in outputs, decisions, and iterations in the different stages of the design process. Iterations are inevitable in the early stages of design due to the fact that the design task is typically still under-constrained. Finally, it was reasoned that design progresses at a macro-level based on a micro-level cycle of analytic and synthetic human activities. The outcome of this project was an innovative (modular, flexible, and cost-optimal) warehouse design concept that was client approved.

The second case study addressed the methodological aspects of designing energy and cost efficient buildings in the conceptual design. Specifically, the focus was on steps, activities, and relationships. The new design model was used to align the three design methods, the integral morphological C-K design method, the Taguchi robust engineering method, and BIM. As an outcome, the new model-based approach made it possible to design more energy efficient buildings at a reduced level of initial investment and with low sensitivity to noise factors. The results achieved were significantly better than the figures for the constructed facility and those reported in the original study.

In the third case study, the new design model was used to improve design management practices in a design company. The new design model together with the design management framework became the baseline for introducing interventions. The longitudinal case study progressed through two iterations. The evaluation of impact through focus group interviews and a macro-analysis of projects demonstrated many improvements. The far-reaching consequence was that the company had become more capable of delivering projects successfully. Overall, both quantitative and qualitative improvements were witnessed.

The first and second case studies had several implications. In the first case study, the new model became the common framework for the design team, thus establishing a common understanding of the design process. Although causality was an essential part of the design process, the focus in the early stages of design was on the interpretation of the needs, use functions, and expected characteristics of a building. In the second case study, it was argued that the new design model could be used not only to study and understand existing methods but also to develop new ones. The conceptual design stage of the design of energy and cost efficient buildings is oriented towards the application of methods and functions. Thus, the focus is on the technical aspects of building design – i.e., causal considerations of designing. Companies developing applications for dynamic energy simulations should include functionality which makes it possible to assess the impact of variations in noise factors on building performance. In the third case study, the general implication was that design managers and designers should be involved in the process of action research to gain their full commitment. A common framework is needed to facilitate this process. Finally, a company needs to implement continuous improvement practices to sustain development.

On the whole, although the results cannot be considered conclusive, the three case studies demonstrated noteworthy improvements upon the implementation of the new design model. Further evaluation of outcomes is presented in the next chapter together with the general fulfillment of success criteria (defined in Chapter 2). Also, the new design model is compared with other general theories of design.

The whole [scientific] process resembles biological evolution. A problem is like an ecological niche, and a theory is like a gene or a species which is being tested for viability in that niche.

David Deutsch

7. Evaluation of Research Outcomes

In this chapter, the new design model, the main output of this research, is compared to other contemporary design conceptualizations, mainly those claiming to be general or unified theories of design (section 7.1). Research outcomes are then evaluated against the industrial and academic success criteria defined in sub-section 2.2.2 (section 7.2). Finally, the general implications of this research for design and design management as well as its limitations are discussed (section 7.3). Finally, a chapter summary is provided (in section 7.4).

7.1 Comparison with Other Design Models

In this section, the new design model is compared with other contemporary design theories and models in the general design literature. Only those design theories which are well-known or claim to be unified theories of design were selected for comparison: the function-behavior-structure model (Gero 1990; Gero and Kannengiesser 2004), axiomatic design (Suh 1998), C-K (concept-knowledge) theory (Hatchuel and Weil 2003; Hatchuel and Weil 2009), parameter analysis (Kroll et al. 2001), V-model (Forsberg and Mooz 1992; Forsberg and Mooz 1998; Forsberg et al. 2005), and human-centered design (Giacomin 2014). Despite the fact that these theories and models are supposedly addressing the same phenomena, they are actually very different (Chen et al. 2015): the domains, entities, reasoning patterns, and even the definitions vary remarkably. Here, the fundamental concepts and principles of each concept and model are briefly reviewed and then compared with the main characteristics of the new design model.

To recap what was stated earlier (see sub-section 3.1.4), the most fundamental characteristic of the new design model is that it considers the methods of design inquiry (modes of resolution and composition) or processes of things (what happens to information and material) inherently analytic or synthetic. Analysis and synthesis are the metaphysical and epistemological theories underlying the conceptualization of design activity. Another characteristic of the model is the way in which analysis and synthesis, considered structurally similar, mirror each other and yet, as processes, flow in opposite directions. Analysis starts with what is first for humans (complex things) and ends with what is first in nature (simple things), whereas synthesis proceeds in the opposite direction, from simple to complex things. Rhetoric is concerned with what is first and last for humans, and the method of analysis with what is first and last in the nature. Therefore, rhetoric addresses the interpretative, and the method of analysis the causal dimension of designing. These differences characterize design contexts (general, user, and artefact contexts), design stages, iterations, the causal structure of transformations, and the modes (subject and object-oriented) and types of mental and external activities. This forms the baseline for comparing the different design theories and models with the new design model.

7.1.1 Function, Behavior and Structure Model by Gero

Though there are many models based on function-behavior-structure (FBS) ontology, such as the model by Umeda et al. (1996), here the well-documented one proposed by Gero (1990) was chosen for comparison. The groundwork for the development of the FBS model was laid between 1984 and 1986 during a series of lectures and seminars at Carnegie-Mellon University and Xerox PARC. The first version of the FBS model was published in a special design issue of AI Magazine (Gero 1990). The following axiom guided the construction of the new model (Gero and Kannengiesser 2014): "The foundations of designing are independent of the designer, their situation and what is being designed". On the basis of this axiom, two hypotheses were put forward (Gero and Kannengiesser 2014): all artefacts can be represented uniformly, and all designing can be represented uniformly.

Key Concepts and Principles

According to FBS theory, designing consists of eight transformations, of which one is comparison: the elementary transformation of requirements (R) into functions (F), functions into artefact behavior (B_e, expected), artefact behavior into structure (S), structure into behavior (B_s, based on structure), and finally, structure into design descriptions (D – external representations of solutions) for designing and making an artefact. The model makes a distinction between expected behavior and the actual performance of the system derived from structure. More generally, FBS defines designing as a progression between observable input and output states, as embodied in design representations (Gero and Kannengiesser 2004). The external representations, design prototypes as epistemic devices, help designers learn how to connect the different states of designing (Gero 1990). Past prototypes guide new designs, acting as the constructive memory of the designer, while new artefacts can lead to the emergence of new design prototypes. The relationship between prototypes is often hierarchical (Gero 1990).

Between 2000 and 2004, Gero and his colleagues further developed the model in a series of papers, incorporating concepts on situated cognition (Gero and Kannengiesser 2004). The main idea was that designing involves interactions between three worlds (Clancey 1997): the external world (things outside the designer), the interpreted world (internal to the designer; representation is constructed via sensory experiences, percepts, and concepts of the external world), and the expected world (the imagined world). The three worlds are related through three classes of interactions (Gero and Kannengiesser 2014): interpretation – the transformation of variables sensed in the external world into sensory experiences, percepts, and concepts of the interpreted world; focusing – formulation of a goal; and action – affecting the external world by changing it. The typical design cycle is a movement from the external world to the interpreted world and from the interpreted world to the expected world and back to the external world.

Additionally, Gero and Kannengiesser introduced a new elementary step, the 'push-pull' processes of interpretation and constructive memory; i.e., processes driven by experience ('push') and processes driven by some of the agent's current interpretations and expectations ('pull') (Gero and Kannengiesser 2014). The new situated function-behavior-structure framework was proposed together with 20 elementary design steps mapped onto the initial eight types of transformations and comparison (Gero and Kannengiesser 2014): formulation, synthesis, analysis, evaluation, documentation, and reformulation type 1, type 2, and type 3.

Comparison

Here, the new design model is mainly compared to the original FBS model by Gero (1990). The aim of FBS theory is to tame the complexity of designing by rationalizing the design process, specifically, by describing product-centered transformations and iterations between the different states of design knowledge.

First, the difference between FBS definitions of analysis and synthesis and those of the new design model need to be clarified. In fact, modern design literature has an understanding of these terms diametrically opposed to what they signified in the ancient conception of the method of analysis (Kroll and Koskela 2015). In the ancient view, analysis was a process of discovery and resolution, and synthesis was the construction and proof of the thing sought. In modern design literature, synthesis is the process of discovery, and analysis is a study of the problematic situation and the rational stage of deducing behavior from the structure (Codinhoto 2013; Kroll and Koskela 2015).

According to FBS theory, there is a mirroring between the steps related to the requirements, function, and behavior (expected), on the one hand, and structure, behavior derived from the structure, and documentation, on the other. However, unlike the new model, the FBS model does not describe the stages related to construction (assembly of sub-designs into wholes). The reason is that design is reduced to the cognitive aspects of designing and not seen in the context of production phenomena.

Although design starts with requirements, according to the FBS model, the requirements are assumed to be given. The interpretative dimension of design, concerned not only with designing with humans but also with designing for humans, is not a part of the model. The goals and ways of use needed to define functions (requirements) have not been defined in the model. Thus, the FBS model is focused on the technical, causal conceptualization of designing. Similarly, Vermaas and Dorst (2007), in their critique of FBS theory, argued that the intentional descriptions of acts and mental states (goals, desires) of users had not been captured in the model. They further argued that this was the reason for the confounding definitions of function (either teleological, user activities, or device functions) and behavior (conceptual or structural) over time.

As a micro-model, the FBS design theory does not define the stages of designing which emerge from the human effort of applying the dominant modes and types of different mental and practical activities in specific stages of transformations (see sub-sections of 4.2.2). The FBS model defines four kinds of iterations: $B_e \rightarrow S \rightarrow B_s \leftrightarrow B_e$; $S \rightarrow S$; $B_e \rightarrow S \rightarrow B_e$; and $F \rightarrow B_e \rightarrow S \rightarrow F$. However, in the FBS model, no generalization of iterations is provided. The new model defines three types of iterations: the progressive, corrective, and managerial. As analysis and synthesis are assumed to mirror each other in the new model, it is argued that there is no essential difference between the $S \rightarrow S$, $B_e \rightarrow S \rightarrow B_e$, and $F \rightarrow B_e \rightarrow S \rightarrow F$ iterations. These are either progressive or corrective, leading to a change in the assumptions made about the function or behavior.

The FBS model emphasizes the causal structure of transformations, i.e., the movement between the different states of design knowledge about the artefact. Except for the implementation and construction stages and stages related to the interpretative dimensions of designing, there is still a great deal of similarity between the FBS model and the new model.

Finally, mental and especially practical activities have been oversimplified or left out of the FBS model. In it, activities consist of the eight types of transformations and one comparison, and they are not related to the fundamental types of reasoning and acting in analysis and synthesis. Unlike the FBS framework, the new model developed in Chapter 5 defined the dominant modes and types of situated mental and external subject- and object-oriented activities characterizing the different stages of design, transforming the design from one state to another following a causal structure.

7.1.2 Axiomatic Design by Suh

The axiomatic design (AD) theory was developed by Suh Nam Pyo at MIT at the Department of Mechanical Engineering in the 1990s. The first International Conference on Axiomatic Design (ICAD) was held in 2000. Axiomatic design (AD), which assumes that design is a systematic effort, focuses on a formalism of the design process (Suh 2001). According to AD, design begins with an explicit statement of 'what we want to achieve' and ends with a clear description of 'how we will achieve it.' When no satisfactory solution for the functional requirement is found, either a new idea must be generated, or the functional requirement must be changed (Suh 2001).

Key Concepts and Principles
The main components of the axiomatic design are domains, axioms, hierarchies, and 'zigzagging'. The domains, which separate different design foci (Suh 2001),

are the following: the customer domain (CD), the conceptual domain (CoD), the physical domain (PD) and the process domain (PrD).

Design begins with the identification and clarification of customer needs (attributes) in the customer domain (Suh 2001) and progresses through design transformations to functional descriptions. In AD design is seen as a pair-wise mapping ('zigzagging') between adjoining domains. The 'zigzagging' progresses from the highest level of abstraction to the lowest. The different levels of hierarchical dependencies reflect the recursive nature of design – upfront decisions constrain the design space downstream (Ullman 2009). At the higher level, the design parameters are conceptual, and decomposition proceeds until the parameters contain enough information for implementation in a medium (Suh 1998). In summary, in AD designers follow these steps (Suh 2001): know or understand customer's needs (characteristics); define the problem (function) to be solved to satisfy the needs; conceptualize the solution (design parameters) through synthesis; perform an analysis to optimize the proposed solution; and check whether the design meets the original needs of the customer.

In the AD process, two axioms must be followed to create a robust design (Cochran et al. 2000): "the independence axiom – maintain the independence of functional requirements, and the information axiom – minimize the information content of the designs". The former means that in a robust design, functions are uncoupled, functional requirements (FR) are orthogonal to each other, and a unique solution can be defined. A design is still acceptable if the resulting equation matrix is triangular or decoupled, where solutions to functions must be developed in a specific sequence. Any other configuration of a design matrix indicates a coupled design and should be avoided (Suh 2001). The information axiom provides a quantitative measure of the robustness of a design. In the simple case of a one-FR, one-DP design, the information content is defined as being the logarithm of the inverse of the probability of achieving the desired value for the FR. Thus, the information content represents the likelihood of meeting the functional requirement(s).

Comparison

As in the case of FBS theory, axiomatic design theory follows the general trends in the problem-solving tradition of design conceptualization. In AD, the meaning of the terms analysis and synthesis is diametrically opposed to what they signified in the ancient conceptions of the method of analysis and synthesis. In AD, the unity of the two directions of analysis and synthesis is not defined. Furthermore, although the first domain is the customer domain, interpretations of the goals and ways of use have not received any attention. In this respect, AD is somewhat similar to the method of analysis, as it assumes the problem is given (customer characteristics), focuses on defining what is sought (function), and delivers a solution. More specifically, it is argued here that AD theory addresses the resolution stage of the method of analysis, focusing on the embodiment of the artefact in structures and processes.

The AD theory does not describe the different stages and iterations of designing. The focus in AD is on the recursive, hierarchical processes of decomposition. The causal structure is defined as a movement between adjoined states of design, mainly between the CoD and PD and between the PD and PrD. Additionally, although zigzagging seems to bear similarities to regression and decomposition, mental and practical design activities are not explicitly defined.

The fourth domain in AD is the process domain. Design parameters in the physical domain need to be mapped to process characteristics in the process domain before making the artefact. This approach differs from that of the method of analysis, which considers the process domain unproblematic. In the new design model proposed in this work, the process domain is operational in the implementation stage, where design embodiments have to be detailed for fabrication in the factory or production on site in the building project context.

In summary, AD is also a very abstract model of the design process, as it has left out many inherently important dimensions of designing. The focus is on the formal/mathematical description of different recursive states of the design process. In this process, designers are guided by the two given axioms, and adhering to these should lead to a robust design.

7.1.3 Concept–Knowledge Theory by Hatchuel and Weil

The C-K theory was introduced by Hatchuel and Weil (2003; 2009), and has gained significant academic and industrial interest over the last 10 years (Agogué and Kazakçi 2014). The initial inspiration for the development of C-K theory came from advanced set theory, a formal study of particular objects (sets) and their properties. Later, category theory and 'forcing' were used to further refine C-K formalism (Hendriks and Kazakci 2011). Due to its highly abstract nature, it has been considered a unifying language, facilitating dialogue between design disciplines, independent of the specific objects of design and designing (Le Masson et al. 2017). In contrast to rule-based design theories and methods, C-K theory focuses on the elimination of the cognitive 'fixation' of ideas, while addressing the difficulty of defining the starting point of the design task (the 'specification', 'program', and 'brief') (Le Masson et al. 2017). Thus, central to C-K theory is the expansive reasoning of the designer (Hatchuel et al. 2009; Kazakçı et al. 2008), i.e., the creative generation of new definitions and objects by conceptual expansion of design ideas (expansive and restrictive).

Key Concepts and Principles

In C-K theory, designing is an interaction between two "spaces", the space of concepts (C) and the space of knowledge (K). Le Masson et al. (2017) describe these spaces as follows: the propositions of K space are characterized by the fact that they all have a truth value (true or false); in C space, as yet unknown objects are developed, i.e., the propositions related to objects whose existence is still undecidable, on the basis of the propositions available in K.

The general schema of C space takes the form: "there exists a (non-empty) class of objects X for which a group of properties p_1, p_2, p_k is true in K" (Le Masson et al. 2017). The set-based formulation of C-K theory states that a concept can be considered a particular kind of set (a C-set) for which the existence of an element is undecidable: the proposition that "a C-set is empty" or "a C-set is non-empty" cannot be decided in K (Le Masson et al. 2017). In C space there cannot be an inclusion relation (which holds only at the moment the existence of elements is proven in K space). Instead, there is a partial order relationship forming a tree-like structure (Le Masson et al. 2017). Thus, C-space is a progressive stepwise generation of alternatives, generally undecidable propositions before conjunction can be interpreted as a solution (Agogué and Kazakçi 2014). One only knows whether a solution in fact exists when the design is complete.

The general schema for K space is based on free parameter theory (Le Masson et al., 2017), which can be modelled using simple graph structures, rigid taxonomies, flexible object structures, specific topologies, or Hilbert spaces if there are stochastic propositions in K space (Le Masson et al., 2017). From the point of view of C-K theory, propositions that are decidable (have a truth value) are distinguishable from those that are not decidable. In practice, this means that although the content of K space might be different for design disciplines, the logic is the same, the aim being to prove that something exists or not (Le Masson et al. 2017).

According to the C-K theory, the design process is a movement from initial knowledge to initial concepts (a desirable but unknown object whose construction cannot be decided using available knowledge), which are manipulated and verified before becoming new knowledge. Designs are rigidly defined only when the design has been appropriately verified as a suitable design solution (Salustri 2014).

Design progresses within and between the C and K spaces through operations. C space evolves by partition, and K space by expansion (Le Masson et al. 2017). Design commences with an undecidable proposition (concept C_0), and through partitioning, attributes are added. In C space, there are two types of transformations, the transformation of the concept and the transformation of knowledge. Transformations continue until a proposition derived from C_0 becomes decidable in K′ (i.e., when the proof of existence is obtained) (Le Masson et al. 2017). K space is expanded through learning, experimentation (e.g., the development of prototypes), and (re-)modelling until a decidable concept is obtained in K. The partitions resulting in C space are tested in K space. The expansion of K space is not necessarily related to the C concept, as a surprise discovery of something new is always possible (Le Masson et al. 2017).

Four elementary operators have been introduced to formalize the operations of partitioning and expanding, two involving a change in the internal structure of the space (K ➔ K and C ➔ C) and two involving the action of one space on another (K ➔ C and C ➔ K). Le Masson et al. (2017) describe the four operators as follows. K ➔ K is the standard operator (e.g., deduction, decision, optimization) for deducing new knowledge. K ➔ C is a disjunction operator for generating new undecidable propositions using decidable propositions in K (concepts C_0 or C_{k+1} are the results of the disjunction). Salustri (2014) provides the following example: “given knowledge items x and y, but no further knowledge about x and y, one might create a concept consisting of $x \wedge y$, or $x \Rightarrow y$”. C ➔ K is a conjunction operator for creating decidable propositions on the basis of undecidable propositions. Salustri (2014) states that these operators transform a concept into knowledge through some action to establish a logical status in K space. The

C ➔ C operator generates undecidable propositions on the basis of other undecidable propositions (using only C propositions). It is used, for example, when one seeks to obtain as complete a partitioning as possible. The undecidable propositions in C space are advanced only by comprehension.

A partition in C space is either restrictive or expansive. Le Masson et al. (2017) described a restrictive partition as one based on the properties of a known object or the properties that are compatible with it (which then function as a constraint). An expansive partition (involving imagination, inspiration, analogies, or metaphors) assigns new attributes to the object not compatible with known objects. Gero (1990) categorized this as creative design (where new variables are introduced). Expansive partitions have two implications (Le Masson et al. 2017): they lead to the revision of the definition of objects (the 'fixation' of ideas), and they steer exploration towards new knowledge not deduced from available knowledge.

Before the comparison, a few interpretations should be considered. Hendriks and Kazakçi (2010; 2011) proposed an alternative formulation of C-K theory, design tableaux, based on the well-known method of semantic tableaux (a decision procedure for sentential and related logics, and a proof procedure for formulae of first-order logic). Hintikka (2012) analyzed the compatibility of the method of analysis and semantic tableaux and concluded that "the ancient Greek method of analysis has a rational reconstruction in the form of the tableau method of logical proof". This suggests that there is an overlap between the method of analysis and C-K theory.

Koskela et al. (2014) pointed out another similarity between the method of analysis and C-K theory, namely, the starting and end points. Both conceptualize the starting and end points as qualitatively different. The starting point is an undecidable proposition which becomes a known, decidable proposition when the design is complete.

Comparison

However, if C-K theory and the method of analysis have several similarities, possessing the same logical structure (semantic tableaux) and starting and end points, then what is the added value of the new design model, given that it is based on the method of analysis?

Analysis and synthesis, as processes of things and methods of inquiry, are not the ontological and epistemological concepts underlying C-K theory. Though C and K spaces co-expand, there is no structural mirroring between the two streams of designing. Because the design process has been abstracted away, the theory does not specify the different stages and modes and types of mental and external activities required to take a design from one state to another in the causal structure (within the different design stages). However, understanding how designers reason and behave is the only way to comprehend design (Rittel 1987).

In C-K theory, iteration is conceptualized as a movement between conceptual and concrete propositions, i.e., the movement between the different truth values of knowledge, and is thus either progressive or corrective. Finally, C-K theory focuses entirely on the causal considerations (elements, properties, and relationships) involved in designing a new artefact. C-K theory does not define the interpretative dimension of designing.

According to Hendriks and Kazakçi (2010), a key issue in C-K theory is the status of 'knowledge', and they proposed applying constructivist logic. This means that a proof of C from K is a construction, a recipe to construct an instance of C_k based on the constructions that exist according to K (Hendriks and Kazakçi 2010). The reason is that the design process has been abstracted away. The construction of figures to demonstrate a problem or prove a theorem has always been central to the method of analysis. Netz (2003) even argued that figures form an essential part of demonstration and proof (see Chapter 4).

7.1.4 Parameter Analysis by Kroll

The initial conceptualization of parameter analysis (PA) as a conceptual design method for adopting a design solution in a specific context was developed at MIT in the 1970s (Kroll et al. 2001). According to Kroll and Koskela (2015), PA conceptualizes the iterative and reflective nature of the design process: "*This model of the design process is in coherence with Schön's reflective practice paradigm (Schön, 1991), including the notion of dynamically framing the problem to discover new aspects of it, generating moves towards a solution, and reflecting on the outcomes.*"

Key Concepts and Principles

As a descriptive model, PA describes the back-and-forth movement between two spaces: the concept space and the configuration space. The 'parameters' in the concept space represent either functions, ideas, or other conceptual issues (such as fundamental concepts of physics, analogies, and other meaningful relationships). Decisions in the concept space guide the movement from one point to another in the configuration space (Kroll and Koskela 2015), which is a physical description of the evolving design consisting of diagrams, sketches, and other representations. Movement from the concept space to the configuration space is the actual construction of the idea in specific media (a sketch, calculations for rough dimensioning, and even crude physical prototyping). A new construction can also stimulate new input to the concept space. The movement from the configuration space back to the concept space is an abstraction or generalization (Kroll and Koskela 2015).

As a prescriptive model, PA defines three steps (Kroll et al. 2001). Parameter identification (PI) involves the generation of a new design parameter, i.e., a new or improved concept/idea connected with the issues that are most important at any given moment of the design process. Creative synthesis (CS) is the creation of a physical configuration based on the concept/idea generated in the PI step. Evaluation (E) is a movement from physical realization in the configuration space to the parameter in the concept space. The design process begins with a concept/idea in the PI step, proceeds through a sequence of PI, CS, and E steps and terminates with an E step when the design is complete. However, as failure is part of the design process (fundamental to the learning process), the three-step process might be repeated several times (Weisbrod and Kroll 2017). Iterations make it possible to advance the design, correct problems or implement changes, and coordinate within a process or between a process and its context (Wynn and Eckert 2017). Every iteration is a co-expansion of concept and knowledge spaces, not just a search limited to available knowledge, as it is in the case of functional and morphological analysis (Kroll 2013).

Kroll and Koskela (2015) also compared PA to the method of analysis. According to Kroll and Koskela (2015), the evaluation step corresponds to the deductive reasoning step of "given structure, find behavior", followed by a decision to improve, abandon, or confirm the configuration (Kroll and Koskela 2015). When a problem in the configuration is revealed at the evaluation step, the designer moves back to the parameter identification step to transform or re-interpret the given problem. Re-interpretation means that the original problem might be converted into another form or examined from a different perspective, and regressive reasoning would lead to the proposal of a new parameter (solution). Thus, parameter identification in PA has two meanings from the perspective of the method of analysis, transformational/interpretational reasoning and regressive reasoning (Kroll and Koskela 2015). Next, the designer continues with a creative synthesis consisting of two operations: regressive reasoning (particularization) of "given (desired) behavior, find structure, corresponding to the ancient analysis" and integration of the current specific hardware in the overall configuration, i.e., composition in synthesis (Kroll and Koskela 2015). The design process then returns to the evaluation step.

Comparison

Firstly, it is important to recognize that PA is a micro-model of the design process, conceptualized from the perspective of an individual designer. Secondly, this conceptualization of design is based on observations of how designers actually work. Thirdly, as Kroll and Koskela (2015) have already compared PA with the method of analysis, on the basis of which they have also further developed it, the task of comparing PA with the new design model has been simplified.

According to the new interpretation based on the method of analysis (Kroll and Koskela 2015), the steps in PA have been aligned with the ancient conceptions of the methods of analysis and synthesis. However, the relationship between the steps in the concept and solution spaces are asymmetrical. In PA, there is an extra decision-making step in the synthesis. Thus, the proposed prescriptive model in Kroll and Koskela (2015) contradicts a fundamental principle in the method of analysis, the unity (structural similarity) of the analysis and synthesis. This is because PA does not include the interpretative dimension in the model. Decision-making requires judgment and thus falls into the rhetorical conceptualization of design.

As PA is a micro-model of designing, the design stages are not included in the classical sense. As in the case of C-K theory, in PA, the designer moves between the concept and knowledge spaces, mediated by three steps: parameter identification, creative synthesis, and evaluation. The design iteration is a full cycle from parameter identification to creative synthesis, to evaluation, and if necessary, back to parameter identification. PA conceptualizes two types of iterations, the progressive and corrective. PA does not define the causal structure of transformations but proposes an abstraction which only involves the process steps.

Regarding the different types of mental and practical activities, the transformational/interpretative dimension of reasoning was combined with regressive reasoning in the parameter identification step. This might be attributed to the neglect of the interpretational dimension, which defines the problem setting (context) and solution framing. Thus, PA is a technical, object-oriented conceptualization of design activity.

7.1.5 Systems Engineering V-Model by Forsberg

The V-model (named after the shape given to the depiction of the development process) was initially developed at NASA in the 1950s to describe the project lifecycle[8]. Its development was motivated by the limited availability of commercial off-the-self (COTS) products. Furthermore, the development of the V-model stemmed from practical needs to address high levels of risk and issues of reliability (Forsberg and Mooz 1998).

Key Concepts and Principles

The V-model represents system evolution[9] as a whole. Different types of V-models have been defined: a V-model for systems engineering processes, one for system architecture, and one for system entities. A dual V-model, which combines system architecture and entity models, has also been proposed. In the left leg, the systems engineering process V-model defines four stages before fabrication, assembly, and coding to build-to documentation: (1) understand user requirements (develop system concept and validation plan); (2) develop system performance specification and system verification plan; (3) expand system specifications into configuration items (CI) design-to specifications and a CI verification plan; (4) evolve design-to specifications into build-to documentation and inspection plan. The right leg mirrors the process phases in the left leg, and the focus is on integration, verification, and validation activities.

Time and project maturity in the V-model progresses from left to right (Forsberg et al. 2005). At each point in time, depending on the needs of the team to make reliable decisions, upward and downward iterations are encouraged in the left leg to allow the study of opportunities (including the study of architectural issues), and in the right leg to allow the assessment of risks and the feasibility of technical solutions (including anomalies). In the upward iteration, it is recommended to go all the way up to the user and user requirements, and in the downward iteration, all the way down to the lowest-level hardware component. Changes in customer and user requirements may require changes in the baseline and design-to artefacts or the revisiting of all gates, activities, and artefacts.

[8] It is acknowledged that prescriptive design models, such as the one by Pahl and Beitz (2007), that resemble the V-model and are compatible with it (Biahmou 2015), exist. However, the V-model was chosen due to the explicit inclusion of stages related to the artefact making and integration.

[9] Forsberg et al. (2005) suggests that the V approach is consistent with iterative evolutionary software development processes, requiring the use of flexible and robust architecture to adapt to evolving requirements and combining risk and client-driven iterative planning.

The results of off-core activities are not baselined; only core decisions are included in configuration management (Forsberg et al. 2005).

The development process in the left leg is dynamic, and iteration is at all levels, allowing for the study of user needs, the investigation of alternative concepts, the performing of analyses, the building of models, and the conducting of evaluations, and may be continued for as long as desired, subject to customer schedule, budget and object constraints. The left leg of the V-model consists of activities involved in the definition and decomposition of requirements and solutions, and this in turn is the basis for the planning and selection of the verification and validation methods to be implemented in the right leg (Forsberg et al. 2005). System decomposition is "the hierarchical, functional, and physical partitioning of any system into hardware assemblies, software components, and operator activities that can be scheduled, budgeted, and assigned to a responsible manager" (Forsberg et al. 2005). System definition is "the design to, build to, and code to artifacts that define the functional and physical content of every entity" (Forsberg et al. 2005). With every new design stage, maturity increases, and concept and design iterations decrease and eventually stop. This marks the beginning of system realization in the right leg.

In the right leg, the process of integration and consecutive verification and validation occur at every successive level. Solutions are verified and validated through selected methods against corresponding requirements defined in the left leg, proving that designs meet the specification and demonstrating that users are happy. The methods of verification used in the left leg are analysis, inspection, demonstration, and test. The anomalies detected should be identified, assessed, and resolved. The decision to waive or allow a deviation from requirements is context-specific and must be negotiated with the customer (Forsberg and Mooz 1998).

On the basis of the V-model, the following important concepts have been developed: the use of tactics, baselines, project cycles, requirements traceability, sequencing of phases, and usage of design-to and build-to artefacts (Forsberg et al. 2005). However, further discussion of these different concepts is beyond the scope of this comparison.

Comparison

Out of all the other design conceptualizations, V-model is the only macro-level process model that explicitly considers the making of the designed object.

Although not conceptualized as analysis and synthesis, the left and right legs in the V-model are assumed to mirror each other. In that sense, the V-model can be considered a contemporary instantiation of the method of analysis. In the V-model, design begins with the identification of users, their needs, and the definition of the concept of operations (ways of use) with a view to the specification of functional and performance requirements. Thus, the V-model is the only model out of the other design theories and models addressed before that explicitly considers the interpretative dimension of designing, i.e., designing with and for humans. The left and right legs of the V-model consist of four mirroring stages. At the bottom is the actual making of individual configuration items. In the V-model, the problem-solving iterations in the left and right legs should ideally run all the way up to the users, user needs, and the concept of operations and down to configuration items at the lowest level. Iterations between the left leg and right leg of the V-model are also possible. When anomalies are identified in the right leg through the verification and validation processes, changes in the designs may be needed. The system architecture and entity V-models describe the technical system-centric causal structure of design transformations.

The main difference between the new design model and the V-model is that in the V-model, the different modes and types of mental and practical activities are not defined. However, as has been asserted before, understanding how designers reason and behave is probably the only way to comprehend design. This is probably the reason why Forsberg's definition processes in the left leg are equivalent to the development of design-to, build-to or code-to artefacts, i.e., documentation of the functional and physical content of each entity. However, this is inconsistent with the philosophical understanding of analysis and synthesis. Although design models (or prototypes, as Gero (1990) argues) are qualitatively different from the real object, any externalization from the mind to the world, including the construction of models, is the communication and making of objects in a medium. This means that fundamentally it is still a process of synthesis. Thus, although the V-model defines the project level (macro) and end-to-end flows of activity models (meso) that occur during the different phases of design, it does not specify individual situated mental and external subject- and object-oriented activities.

7.1.6 Human-Centered Design

The last approach considered is human centered design (HCD). Since the mid-20^{th} century, due to the maturation of technologies (Taura and Nagai 2017), designers have moved away from technology centered approach closer to the end-users of the products of design and engineering. Sanders and Stappers (2008) described the evolution of design approaches: "[…] the changing landscape of design research has become co-designing with your users". Since then there has been a shift in the emphasis of design paradigms. Giacomin (2014) described this shift as "[…] the progression of design paradigms which have evolved and prospered over the years starting with ergonomics and moving through human factors, usability, user-centered design, inclusivity, interaction design, empathic design, design for product experience, design for customer experience, design for emotion, emotionally durable design, sensory branding, neuro-branding, service design and finally, most recently, the umbrella paradigm of human centered design". The HCD paradigm has progressed from the psychological and physiological study of humans for designing artefacts to the study of how people interact with, perceive, and experience the meanings they create (Buchanan 2001; Krippendorff 1985). In what follows, user-centered design, co-design (participatory design), and particularly HCD concepts are reviewed, as these are the latest developments and build on earlier ideas.

Key Concepts and Principles

User-centered design was proposed by Norman and Draper (1986) and further developed and operationalized by others (Vredenburg 1999). Vredenburg et al. (2002) proposed the following working definition for user-centered design: "[...] the practice of the following principles, the active involvement of users for a clear understanding of user and task requirements, iterative design and evaluation, and a multi-disciplinary approach". User-centered design gained increased attention and acceptance after the publication of "The Design of Everyday Things" (Norman 2013). It is a design process framework which considers usability, user characteristics, contexts, activities and workflows central aspects in every stage of the design process, increasing the usefulness and usability of artefacts (Norman 2013).

User-centered design methodology is focused not only on envisioning the uses of the artefact but also on the validation of assumptions through user-centered tests. Furthermore, Norman made the following recommendations concerning user-centered design practices: the simplification of the task structure, making things visible, mapping the relationships between the intended results and required actions, and exploiting and embracing system constraints. Later, Norman (2004) expanded user-centered design to include emotions. These ideas are now widely acknowledged in the design domain. However, there are also critical views of user-centered design (Giacomin 2014): "designing for a 'user' usually involves optimizing the characteristics of the product, system or service based on a set of fixed preconceived cognitive plans and schema".

Co-design (also known as participatory design; initially known as co-operative design), rooted in Scandinavian work practices and the involvement of trade unions in the 1960s and 1970s (Sanders and Stappers 2008), is now used in a variety of settings on many scales, e.g., in urban design, (landscape) architecture, product design, and planning. Recent research has argued that co-design environments induce more innovative concepts and ideas (Mitchell et al. 2016).

Co-design is a creative design approach which involves all project stakeholders in the design process (Trischler et al. 2018). Steen (2013) described co-design as "joint inquiry and imagination", where "problem and solution co-evolve". The underlying assumption in co-design is that "it is possible to gain access to the experiencer's world only through his or her participation in expressing that experience" (Sanders and Dandavate 1999). Users and stakeholders are encouraged to share their expertise and "participate in the informing, ideating, and conceptualizing activities in the early design phases" (Sanders and Stappers 2008) with the aim of defining what is to be designed or not to be designed. In co-design, the desire is to envision the use (plan) of the artefact before its actual use (Redström 2008). As a value-centered design approach, participatory design is not only about outputs, but also about changing/developing people, organizations and practices (Gregory 2003).

Instead of centering the design process on individuals or user communities, co-design is built on the idea of collaboration and the team approach (Sanders and Stappers 2008). This means that co-design differs from the user-centered approach in how the design process is facilitated, how long the users and stakeholders are engaged, and the contributions expected from future users and stakeholders (Trischler et al. 2018). In the co-design process, users and stakeholders are empowered and acknowledged as members of the design team (Visser et al. 2005). The identification of proper users and stakeholders and the management of collaborative approaches is a crucial consideration in the co-design process.

In co-design, design tools that encourage joint exploration and dialogue are used – 'tools for conversation' (Sanders et al. 2010; Trischler et al. 2018). The tools used in co-design range from 'make tools', 'design probes', and 'design games' to 'design cards' (Trischler et al. 2018). Additionally, tools for representing current and future states are used to articulate insights, support learning, facilitate communication and collaboration, and maintain empathy with customers (Blomkvist and Segelström 2014).

HCD, an umbrella term for designing for and with humans, has roots in ergonomics, computer science and artificial intelligence (Giacomin 2014), as echoed in ISO 9241-210 (ISO 2010): "Human centered design is an approach to systems design and development that aims to make interactive systems more usable by focusing on the use of the system and applying human factors/ergonomics and usability knowledge and techniques. Human centered design [...] complements existing systems design approaches". HCD is focused on the humans for whom the artefact is intended, to obtain an understanding of their needs, desires, and experiences and to design artefacts that are physically, perceptually, cognitively and emotionally intuitive (Giacomin 2014).

HCD is a way of making sense of things – meaning-making (Krippendorff 1989). According to Giacomin (2014), HCD is a process of answering an incremental set of rhetorical questions: "Quis (who), Quid (what), Quando (when), Quem ad Modum (in what way) and Cur (why), associated with design semantics to structure the growing layers of complexity". On the basis of these questions, Giacomin proposed a human-centered pyramid, with considerations related to human factors (physical, perceptual, cognitive, and emotional characteristics) at its base, and the meaning of artefacts to humans at the top. Designs addressing the top layers of the pyramid have a more significant impact on humans and their lives, their behaviors, and social interactions. This is achieved by challenging their assumptions and pre-established notions. In this respect, HCD differs from user-centered design (Giacomin 2014). In HCD, future users co-create new meaning through common interpretation; a new artefact is not designed simply by interpreting needs based on human psychological and physiological characteristics.

ISO 9241-210 lists the following benefits of HCD: the increased productivity of users and the operational efficiency of organizations; more straightforward to understand and use, thus reducing training and support costs; increased usability for people with a broader range of capabilities and thus increasing accessibility; improved user experience; reduced discomfort and stress; competitive advantage, for example by improving brand image; and contribution towards sustainability objectives (ISO 2010). The six principles of HCD were also outlined (ISO 2010): develop an explicit understanding of users, tasks, and environments; involve users throughout design and development; use user-centered evaluation; use iterative processes; address the entire user experience; and include multidisciplinary skills and perspectives.

In HCD, five key activities, one managerial and four design-specific activities, were also proposed (ISO 2010): the planning of human-centered design; an understanding and the specification of the context of use; a specification of user requirements; the production of design solutions; and evaluation of the design. Furthermore, the standard defines the content and methods of each activity and criteria for designs to conform to HCD approaches. Many of the methods and tools proposed overlap with user-centered design and co-design. For an overview of methods and tools, readers are recommended to see Giacomin (2014).

In summary, designing for intended users and stakeholders has moved from 'designing for humans' to 'designing with humans' and 'designing for humans with humans' and from user-centered design to co-design and human-centered design. Human-centered design is the empowerment of (potential) users and stakeholders to collaboratively explore and imagine co-evolving design problems and solutions by challenging pre-existing understandings. Thus, the central concern in HCD is the interpretation of meaning for humans. Regarding the team approach, different techniques to facilitate collaboration and communication processes have been proposed.

Comparison

HCD is a social conceptualization of the design process. Out of all the models, it is the only one that has focused mainly on the interpretative dimensions of designing. Furthermore, HCD is not conceptualized as a stand-alone design approach, but it is assumed that it will be used within the project lifecycle or in combination with problem-solving approaches. A comparison with the new model follows below.

Regarding design circumstances, HCD considers the different contexts of designing (ISO 2010): the context of use, the context of user needs, and the context of user interface specifications. These can be aligned with the three contexts specified in the new model: the 'context we design within', the 'context we design for' and the 'context of design'. However, it is important to note that HCD takes a 'black-box' view of requirements for the 'context of design', while the new model takes also the 'transparent-box' view of design. Regarding requirements, HCD describes the requirements of the expected workings and behavior of the artefact from the user perspective, while technical conceptualizations describe them from the perspective of causality. The necessary transition or transformation from the former to the latter is described as the process of translating the 'customer's voice' to the 'engineering voice' (De Vries 2009). This is not described in the HCD model but is captured in the new model by the movement from the external to the internal perspective of the artefact.

HCD does not specify the stages/phases of designing, but it does name five key activities. Human-centered design, as ISO 9241-210 states, "[...] is complementary to existing design methodologies and provides a human-centered perspective that can be integrated into different design and development processes in a way that is appropriate to the particular context" (ISO 2010). As in the new model, iteration in the different stages/phases is considered fundamental in

HCD. However, HCD does not define the state changes of design knowledge or the causal structure of transformations. Finally, although HCD specifies activities, it does not articulate their mode and type.

In summary, it is argued that HCD is rather akin to (design) rhetoric. Several of the scholars addressed in earlier chapters and here (Buchanan 1985; Buchanan 2009; Giacomin 2014; Halstrøm 2017; Joost and Scheuermann 2007; Kaufer and Butler 2013), have considered rhetoric or its elements an underlying model for HCD. The central concern of HCD is interpretation, as embodied in the 'designing for humans with humans'.

7.1.7 Comparison Summary

In the design literature, many process models have been proposed (see 4.2.2.10). Models have been created for different purposes and from different perspectives: in the context of use, purpose, function, behavior, and structure. For comparison, design theories incorporating models and addressing the characteristics of the design process were chosen. In particular, the ones claiming to be general or unified theories of design were selected. These models were also chosen because they are well-documented.

The FBS model, AD theory, C-K theory, PA, the V-model and HCD focus on design creativity, complexity, iterations, and social aspects. The FBS model, AD theory, and PA have formalized product-centered descriptions of transformations and individual design activities, including elementary steps (variously named) and design relationships. The FBS model and PA also describe elementary design iterations. Thus, these three theories address the complexity of designing by formalizing design activities, sequences, and iterations. The underlying assumption of these models is that although designing involves novelty, it also involves routine steps, relationships, and structures (Wynn and Clarkson 2017).

C-K theory is the only one out of the five that explicitly aims at formalizing design creativity. It is a high-level abstraction for modelling different states of design knowledge, i.e., the movement between concept and knowledge spaces. The underlying assumption seems to be that design creativity is the most fundamental entity in the design process. The rest of the design process, i.e., how designers reason and behave, has been abstracted away. In the new model, design creativity is addressed as an emergent phenomenon of the design process.

Only the V-model describes project lifecycle processes, incorporating also the sub-processes in each phase of its right leg and left leg. Although HCD specifies design activities, out of all models, only the V-model also conceptualizes design stages/phases (and activities) explicitly related to users, needs, and ways of use, i.e., considers the interpretative dimension of designing. The underlying assumption in the V-model seems to be that the common process framework will help to align participants and their mental models, and this is essential for enabling coordination. The framework should also reduce the probability of forgetting something important, make it possible to teach the design, facilitate planning, and improve communication (Wynn and Clarkson 2017). Thus, the V-model addresses the complexity, iterations, and social dimensions of designing.

However, the V-model falls short of describing the different modes and types of mental and external activities

Like the new model, HCD, without disregarding the need for problem-solving, explicitly connects design activities with the social dimensions of designing. In HCD, the principles of customer focus, user involvement, user-centered evaluation, and iteration focus on the whole, and interdisciplinary design has been articulated.

Finally, although the FBS model, AD, and PA also provide prescriptions for design action, the FBS model, AD, and PA, as well as C-K theory, focus on the description of the generation and communication of conceptual ideas of designing. In the case of the FBS model, conceptual insights consist of a description of situated cognition, the general sequence of transformations, and the usage of design prototypes as epistemic means. In the case of AD theory, conceptual ideas consist of the mathematical formalism of design matrices and the definition of axioms (the underlying truths of the design process). In the case of C-K theory, the entire focus is on the formal mathematical modelling of design creativity.

In **Table 22**, the comparison of the different models is summarized. To reiterate, C-K theory focuses on creativity, while all other design conceptualizations focus on either complexity or design iterations. The V-model, HCD, and the new model also address the social aspects of designing. As was proposed in sub-section 5.4.1, the new design process model is considered self-similar across different levels of processes, at the project level, phase level, and individual level. The V-model addresses the macro- and meso-levels but not the micro-levels of designing. HCD addresses meso-level design activities. The remaining theories consider the micro-aspects of designing.

The ancient conceptions of analysis and synthesis are considered fundamental processes of the inquiry of things (i.e., information and material in the design context). From the perspective of these concepts, current design theories are focused on the product in analysis or the process in synthesis or both, i.e., on the changes the product and/or process are going through. Thus, the process of change of things is related to the kind of causal structure that has been defined by the model. For example, the FBS model is focused on the product, for which a sequence of mental activities, mainly in the analysis, have been defined. AD theory defines product-centered transformations. PA only describes the steps and sequence of the design process. Though HCD does not, according to the standard, describe analysis and synthesis, its focus on analysis and synthesis is evident in the specified HCD activities and expected outputs of each activity. The V-model and the new design model have integrated both dimensions; i.e., they both describe the stages and steps of the design process and what happens to the artefact.

According to the interpretation proposed here, from the perspective of the ancient conceptions of the method of analysis, the FBS model, C-K theory, and PA at least partially reflect the mirroring between analysis and synthesis. In HCD, the cyclic description of the design process to some extent implies a mirroring.

In the V-model and new design model, the mirroring is an underlying assumption. Mirroring encapsulates the idea of moving between subjective and objective claims about the artefact. Only the V-model, as a macro- and meso-model, and the new design model describe design stages.

With the exception of AD theory, the design theories considered here define progressive and corrective types of iterations. The V-model, HCD, and the new design model also define managerial iterations related to objectives, strategies, risks, and uncertainty. In C-K theory, the causal structures involving products and processes is not defined, but the causal structure relating subjective and objective knowledge states is. In all other theories, causal structures focused on either products or processes or both have been defined. Both the new design model and PA focus on describing mental and external activities. PA, however, has not conceptualized subject-oriented activities. In the FBS model, mental activities are oversimplified, and external activities are not defined. HCD describes activities but does not specify their mode or type.

In summary, the new design model proposed in this thesis is more comprehensive than those considered here. However, it must be acknowledged that these other models contain aspects not present in the new model, like the axioms of AD theory or the formalism of C-K theory. However, these models are not on the same level of generality as the new proposed design model, which conceptualizes designing as a human activity, which includes the situated subject and object mental and external activities. This is often the case with unifying theories, which lean towards breadth over depth (Deutsch 2011), and thus, they will generally not include all the aspects of different more specialized theories.

Table 22. Comparison of different design theories and models.

Aspects	Characteristics	FBS	AD	C-K	PA	V-model	HCD	New Model
Focus	Creativity			+				
	Complexity	+	+		+	+		+
	Iteration	+	+		+	+	+	+
	Social					+	+	+
Process Scope	Macro (Project)					+		+
	Meso (Phase)					+	+	+
	Micro (Individual)	+	+	+	+			+
Analysis	Process focused	+			+	+	+	+
	Product focused	+	+			+	+	+
Synthesis	Process focused				+	+	+	+
	Product focused					+	+	+
Analysis and Synthesis	Mirroring	+/-		+/-	+/-	+	+/-	+
	Interpretation					+	+	+
	Causality	+	+		+	+		+
Stages	Specifies stages/phases					+		+
Iterations	Progressive	+		+	+	+	+	+
	Corrective	+		+	+	+	+	+
	Managerial					+	+	+
Causal structure	Specifies causal structure	+	+	+	+	+		+
Activities	Mental	+/-			+			+
	External				+			+

7.2 Evaluation of Outcomes

In this section, research outcomes are evaluated against the defined industrial and academic success criteria. First, the industrial success criteria are addressed based on the practical interventions reported in Chapter 6. After that, the fulfillment of the academic criteria is discussed.

7.2.1 Evaluation of Outcomes for Industry

In this sub-section, the fulfillment of industrial success criteria is evaluated. In the first part, the evaluation is based on the empirical evidence of the practical interventions and results reported in Chapter 6. In the rest, the evalution with respect to the three established success criteria is based on the argumentation. Industrial criteria consist of the following: clarifcaition of a conceptual framework for designing, the operational design model embodying the relationships between different factors, and theory-driven design to improve practices.

Evalution of Practical Interventions
In the first case study, the focus was on the early stages of the design process: the setting up of the project (team formation and process formulation), situation analysis and goal formulation, the establishment of the ways of use and product characteristics, and solution framing. The early stages of the design process correspond to the first three steps in the top-left quarter of a new design model (**Figure 17**). The main focus was on invention and the evaluation of ideas, issues, and requirements based on the given problematic situation and a study of potential users and their needs. Thus, interpretation was the primary driver of the design process. However, the design also involved a study of the possible characteristics of the artefact (the causal aspects of a design).

Designing also involved collective and individual design activities in the different stages of the design process. In the individual and collective design processes, BIM was used to facilitate conversations. The outcome of the design process was a modular, flexible, spatially optimized, cost and energy efficient combined production, service, storage, and office building concept. The warehouse building concept together with the set of requirements became the basis for a traditional design process. Although the project went over time due the fact that the designers were not working on the project full time, the client was satisfied with project outcomes, which were validated on the market through a fictive marketing campaign.

In the second case study, methodological questions involved in the conceptual design of robust energy and cost efficient buildings were investigated. To this end, the instantiated framework helped to align the different steps of integral morphological C-K theory, Taguchi robust engineering, and BIM. On the basis of this alignment, the content of each step was specified: a definition of the ideal function most relevant to the client, concepts and partial solutions for developing complete concepts, implementation, construction, and testing and evaluation of concepts. Compared to the figures for the built apartment building and the results reported in the original study (Pikas et al. 2015), significantly better results were obtained here at a reduced level of energy consumption and with lower noise sensitivity.

In the third case study, the usefulness of the new design model in the design management context was evaluated. With a view to the improvement of practices, the current situation was analyzed, causes were inferred (poor conceptualizations of design and design management), interventions were carried out in two iterations, support was developed for the implementation of the new conceptualizations (new organizational and bonus structures, process models, checklists, meeting templates and structures, and visual controls), and outcomes were evaluated through a focus group interview and a macro-analysis of company projects. On the whole, considerable qualitative and quantitative improvements in design project management, design operations management, change management, resource management, and coordination and communication, as the primary considerations of design management, were achieved.

However, in addition to the industrial outcomes achieved in the three case studies, other outcomes, to be discussed next, can be expected when the new design model is applied in other contexts connected with the designing of buildings.

Conceptual Framework

The new design model defines underlying metaphysical, ontological and epistemological concepts, which can be categorized either as analytic or synthetic. Furthermore, in the new design model, designing as human activity takes place in three specific contexts through different phases of design. The progressive, corrective and managerial iterations are the basis for the progress of the design from one state to another in the design process, i.e., for causal transformations between input and output states.

The analysis starts with what is first for humans and last in nature, framing problems and solutions, and ends with what is first in nature, providing a structural description of solutions. The end of analysis is the starting point for synthesis, which begins with what is first in nature and progresses in the opposite direction toward the production and evaluation of choices. Synthesis is structurally similar to analysis and ends with what is first for humans and last in nature. Epistemologically, analysis makes claims (subjective) about what could be, while synthesis makes claims (objective) about whether something exists or not. The movement between different states of knowledge is mediated by situated mental and external subject-oriented (social) and object-oriented (technical) activities.

Although the evaluation in Chapter 6 is only partial, it is argued here that a fundamental understanding of these basic concepts relevant to the design process has wider practical implications. A good understanding of these concepts can be applied in other contexts of design practice.

New Design Model

Making concepts of designing understandable to practitioners requires the articulation of relationships between different relevant concepts. Specifically, design models embodying the relationships between different factors in the design process can support practitioners in their development of a better understanding of the design process as a whole. Therefore, in addition to the descriptive concepts, the new design model prescribes design action. The new design model defines the relationships between underlying modes of activity (analysis and synthesis), the categories of design activities, contexts of designing, stages and sub-phases together with the causal structure of design transformations, iterations, and mental and external activities. More precisely, the new model defines the normative sequence of contexts, stages/phases, transformations, possible iterations, and mental and practical activities.

In short, design progresses through the stages of invention (problem and solution framing), solution generation (concept and embodiment), implementation (communication and making), development (construction and testing) to delivery and evaluation. The progression from one stage to another is defined by the causal structure of transformations: from goal, way of use, function, mode of action, and embodiment to details in the analysis; and from components, assemblies, sub-systems, behavior, outputs and effects, outcomes, and qualities to customer satisfaction in the synthesis. The transformation between states is enabled by the iterative application of mental and external design activities, which transform information and material. In the three different cases where the new design model was applied, it was operational and usable in the development of practices and support for design and design management processes. Improvements in design and design management were demonstrated.

Furthermore, it is argued in the new design model that processes are structurally similar on different levels. In all case studies, high-level macro- and meso-processes were demonstrated. However, although micro-level models were not directly observed in the case studies, it is not difficult to find micro-level models that support the structural similarity of the multi-level conceptualization of design activity. For example, with the exception of the interpretative dimension of designing, parameter analysis is aligned with the new design model (see 7.1.4). In summary, the definition of relationships between concepts should provide practitioners with a more holistic view of design activity and support the operationalization of design processes in practice.

Theory-Driven Practices

A better understanding of design activity and the basic concepts and relationships of designing should support the development of better practices and lead to value-adding design and design management processes and outputs/outcomes. In the first case study, the common framework made it possible to align the efforts of different disciplines. As an output, an innovative warehouse concept was developed, and its validation (through a fictive marketing campaign) brought assurance to the client that the right concept had been developed. In the second case study, the steps of the new design model were aligned to three different methods used to develop a better energy and cost efficient design concept at reduced levels of energy consumption and with a lower sensitivity to noise factors. This is a matter of particular importance, given that the failure to meet specified performance criteria has become almost the norm in the construction industry. In the third case study, the application of the new design model together with design management concepts helped to develop support for new practices. Different methods and tools (instantiations) were developed on the basis of features of the new design model (see section 6.1). In all cases, improved performance was demonstrated.

7.2.2 Evaluation of Outcomes for Academia

In this section, research outcomes are evaluated against academic success criteria. Academic criteria consist of the following: clarification of a proper philosophical framing, a conceptual framework for design factors, a new design model embodying the relationships between different factors, and theory-driven approaches for improving practices.

Philosophical Framework
In Chapter 3, it was argued that no research takes place in isolation from its general context and prevailing intellectual forces. Throughout chapters 1-3, it was argued that the dichotomization of design conceptualizations into technical and social phenomena came about due to an inappropriate philosophical framing. In the second half of the 20th century, design research followed naturalistic research paradigms: positivist and constructivist approaches.

Positivist research focuses on the solution domain and emphasizes theories, concepts (reason), and observation (practice), which is focused on the verification of theorization. Constructivist research, on the other hand, focuses on the problem domain: the description of different perspectives and the development of consensus. In the constructivist view, reality is constructed through the interaction of actors. However, both paradigms have significant limitations. Positivist design conceptualizations have focused on problem-solving and neglected the importance of framing and re-framing design problems, while constructivist conceptualizations have focused on the latter. These two views were (and still are) recognized as incompatible; this is another reason for the dichotomization. Another limitation is that both research paradigms are concerned with the 'as-is', that is, the presence of the phenomena being studied. However, designs and designing are about the future, how things ought to be. Therefore, it was concluded in this research that the application of naturalistic approaches has limited value in the domain of productive sciences.

The technical and social perspectives should instead be seen as complementary frames of reference. In recent decades, numerous attempts have been made to integrate the technical and social perspectives (Koskela and Ballard 2013; Kroes 2002; Vermaas and Dorst 2007), resulting in new formulations: socio-technical systems, the two pillars of design, the dual nature of design, etc. This was also the direction that was followed throughout this research.

A pragmatist paradigm leaning towards activity-based epistemology was proposed as an underlying philosophical framing which would enable the synthesis of different views. With no pre-established predispositions, pragmatism supports the central idea of change in design, as it is a philosophy of the production of consequences which reflect how things ought to be. In this research, the pragmatist view supported the conceptualization of design activity from the perspective of process metaphysics. Ontologically, different mental and external design activities were categroized into subject and object-oriented activities that transform information and material. Like C-K theory, which models the movement between undecidable and decidable propositions, design epistemology was conceptualized as an inquiry into subjective and objective claims about the design artefact, as created by the application of human effort.

Other similar attempts (Dalsgaard 2014; Goldkuhl 2012; Melles 2008; Rylander 2012) provide further justification for this new perspective, which is expected to contribute to the larger body of design research and support its continued development. The pragmatist framing makes it possible to synthesize descriptive and prescriptive conceptualizations of design activity, and this in turn will have an impact on design practices.

Conceptual Framework

Because the factors relevant to designing and design theorization were already described in section 4.1, they will not be covered here again in detail, but the aim will be to elaborate on more general implications.

First, to reiterate, analysis and synthesis were defined as fundamental concepts which define the method of inquiry and processes of things. Different design researchers subscribe to the different notions of analysis and synthesis, generally, the philosophical and mathematical notions of analysis and synthesis (Codinhoto 2013; Koskela et al. 2014; Kroll and Koskela 2015; Taura and Nagai 2017). The philosophical and mathematical understandings of analysis and synthesis are, however, very different (Kroll and Koskela 2015). Thus, one of the primary outcomes of the proposed new design model is the clarification of analysis and synthesis as fundamental processes of inquiry and things. The new model also provides a clarification of stages, the directions of analysis and synthesis, associated mental and practical activities, relationships, and the states of things. The movement within and between analysis and synthesis reflects the epistemological idea of moving between subjective and objective claims about the artefact.

Furthermore, the two related domains of consideration, namely the problem and solution domains, were defined bearing in mind the interpretative or causal aspects of designing. The design process was accordingly described as a process moving from the client and user perspective to the problem-solving perspective (including the generation of ideas, implementation, and the development of solutions) and back to the client and user perspective. The grouping of different activities according to the causal structure of design transformations (see subsection 5.4.3) is also the basis for the formation of different stages of designing: invention (problem and solution framing), solution generation (concept and embodiment), implementation, development (construction and testing), and delivery (transition and evaluation). This means that there are dominant mental and practical activities in the different stages of designing.

In summary, it is expected that the clarification of these concepts of designing will help advance design research. Not all aspects of the design process made evident by the different design theories and models were considered here (see sub-section 7.1.7), as breadth was sought over depth in the construction of the new model.

New design model
In the academic context, the new design model was envisioned as a means to understand design process dynamics, i.e., the design activity that a designer carries out while designing. Design is a complex phenomenon consisting of situated subject- and object-oriented internal and external activities. The function of the design model is to describe or prescribe the relationships between different factors in the design process. In the new design model, categories of human activity (sensory experiences, perception, conception, deliberation, external and internal actions) were related to the methods of inquiry and processes of things (analysis and synthesis), design contexts, stages, causal transformations, and types of internal and external activities of designing. In comparison with the other design theories and concepts in sub-section 7.1.7, the new design model is more comprehensive. Thus, the explicit description of the relationships between the different factors addressed in this research should help design researchers better understand the dynamics of design.

Theory-driven practices
As design is about producing change, design theories and models need to set standards for the different aspects of the design process. Theory-driven practices should embody a set of prescriptions appropriate for each design practice. Pragmatism, as an activity-based research epistemology, supports the integration of the descriptive and prescriptive aspects of theorization, i.e., how things are and how they ought to be. Furthermore, the pragmatist view implies that a theoretical explanation, which is epistemologically subjective, is the primary driver for the development of practices with practical utility. Thus, central to pragmatist philosophy is the reduction of the conflict between subjective and objective claims, as is characteristic of problem-oriented research paradigms, including Popper's philosophy (Deutsch 2011). Although the present research began by addressing poor practices in the structural and sustainable design of buildings and the management of the processes involved, the first four chapters focused on the development of an explanatory account of design activity based on philosophical concepts and the method of analysis and rhetoric. This supported the operationalization of a new design model, which led to better design and design management practices. Though the evaluation here of practical usefulness cannot be exhaustive, it supports the idea that activity-oriented research paradigms are suitable for developing design theories that are also useful in design practice.

7.3 Discussion

In this section, the results of this research and their implications for design research and design management are discussed. First, the contributions and methodology are discussed. Implications for design research and design management are then addressed.

7.3.1 Contributions

The main contribution of this thesis to the body of design knowledge is the formalization of a new design process model which synthesizes the interpretative and causal and the situated subject- and object-oriented mental and external activities of designing. The application of this new model together with fundamental philosophical design process and design object concepts to a particular design context is argued to provide a new understanding.

In the second half of the 20th century, the two broad conceptualizations of designing were design as a technical activity and design as a social activity. The technical and social traditions of design conceptualization were aligned with the overall tendency of scientific practices, where the positivist and constructivist paradigms of research were the prevailing philosophical views. Because of the adherence to these two distinct and incompatible research paradigms, design theorization evolved into two separate strands. However, since the end of the 20th century, there have been several attempts, with some success, to synthesize these two perspectives, resulting, for example, in socio-technical systems, two pillars of design, and the dual nature of design.

In this thesis, it was argued that these views can be synthesized when design is considered from the process and pragmatist perspectives. More specifically, as depicted in **Figure 35**, the 'designing to function' and the 'designing with methods' as the technical perspective and the 'designing for humans' and the 'designing with humans' as the social perspective are synthesized through the design process.

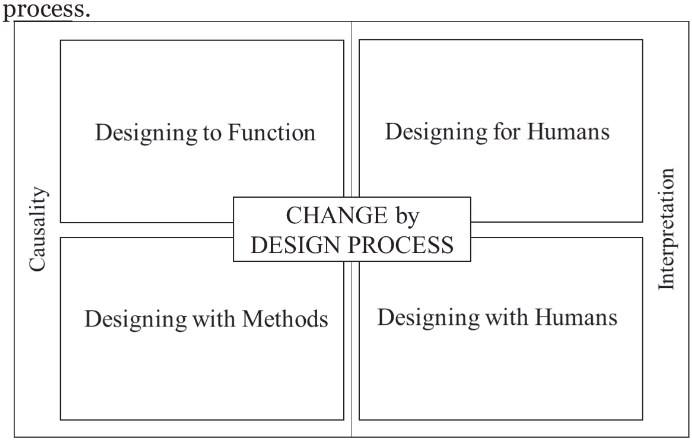


Figure 35. Synthesis of causal and interpretative dimensions of designing through the process perspective.

The second contribution relates to the intellectual history of the discipline of design, engineering, and design management. It was shown that the two views of causality and interpretation of designing could be traced back to Aristotle's productive sciences, which he named *techne*. Aristotle assimilated ideas, concepts, and principles of designing from the method of analysis and rhetoric to describe the productive act. However, with only a few exceptions, contemporary design scholars have either failed to consider or not been interested in considering the method of analysis and rhetoric the underlying models of designing.

In this research, it was then necessary to clarify the philosophical meaning of analysis and synthesis, the stages of geometric problem solving and the development of persuasive speech, strategies and iterations, and internal and external types of design activity.

The third main contribution is related to the clarification of core terms, concepts and their relationships in the context of the design process, including analysis and synthesis, categories of human activity (subject and object-oriented), the contexts of designing, stages and iterations in designing, the causal structure of transformations, and the modes and types of internal and external design activities. This new understanding made it possible to construct a new design model which is more comprehensive than the theories and models addressed in section 7.1.

7.3.2 Research Validity

This research addresses the most fundamental concepts and aspects of designing. Therefore, it is not possible to fully validate the new model directly, but its justification is provided by the fact that the operational and practical methods, tools, and practices developed on the basis of it have proven to be practically useful. The validity of the new design model is demonstrated in four different ways.

First, it was shown that the method of analysis and rhetoric overlap and share many similar aspects with the contemporary design conceptualizations of Simon (1981) and Buchanan (2009). This is justification through *ethos*.

Secondly, when the features of the method of analysis and rhetoric were compared with contemporary conceptions of design, many correspondences were identified, strengthening the argument that the two ancient strategies of inquiry are still relevant (see Appendix II).

Thirdly, it was asked whether the new conceptualization of designing and the new design model support the development of a new understanding and lead to improved performance when applied in specific building design and design management contexts. Methodologically, the new design conceptualization and model were applied in three different case studies through the translation and instantiation of concepts and principles to support practice. Although the results cannot be considered conclusive, the three case studies demonstrated significant improvements.

Fourthly, the new design theory and model were compared with contemporary design theories and models, those claiming to be general or unified theories of design and/or which are well-known and documented in the design literature. Though the new design model does not encompass all the elements of these other theories and models, it is more comprehensive than any of them.

However, even if the initial validation of the new theory and design model is accepted, the validity is still tenuous. Further research is required to refine and test the theory and model.

7.3.3 Implications for Design Management

The new understanding of designing and the new design model have implications for design management. Designing is a complex phenomenon, and so is design management. Design management is influenced by how a design activity is conceptualized. In turn, this is dependent on the particular design paradigm selected and applied when studying and developing descriptive as well as prescriptive concepts and practices.

In this research, design was considered part of the production phenomenon. Although designing is an internal non-routine human activity (see section 4.1), consideration of design in the context of production is justified, as every design is meant to be produced, and all artefacts produced by humans have been designed. Thus, design is embedded in the broader phenomenon of production. Also, designing is situated, placed in a specific context (e.g., society, the environment, or the economy) (Bucciarelli 2002), from which it cannot be removed. This applies also to design and social processes (Halstrøm 2017), which are embedded in activities that are object-oriented (designing to function with methods) and subject-oriented (designing for humans with humans), respectively.

The embeddedness of designing in production and the wider context means that designing always involves aspects and activities beyond individual internal non-routine activities (see sub-section 4.1.4), in particular, aspects and activities arising from designing in collaboration with others and those involved in the creating and streamlining of information. Designing needs to be seen from the flow perspective (Ballard and Koskela 1998); it needs to address the structure of information flows to reduce uncertainty and unnecessary processing times and eliminate waste (unnecessary rework or work that is not value adding). In the flow view, a team approach and design information batch reduction are advocated (Koskela 2000). For example, buildings, as complex products, require collaboration between designers and the coordination of activities and decisions if information flowing through the design process is expected to generate maximum value (Fischer et al. 2017). Therefore, it is important to develop guidelines for the management of design activities, that is, guidelines for the management of designing and the execution and improvement of the design system from the technical and social perspectives.

The new model has practical implications for design management and possibly for design management research. In this research, the focus has been on the theory of design, and the practical implications for design management described in Chapter 6 were more for the purposes of evaluation (and validation). Thus, in this research, no exhaustive treatment of design management has yet been provided. In the following, more general implications based on the findings in the three case studies are addressed first, and implications beyond the direct findings of this research, based on theoretical arguments, are addressed after. The latter can provide directions for future design management research.

In the first case study, the focus was on the early stages of designing. This period is often referred to as the pre-design phase, implying that there is a distinction between the traditional design process and what comes before. For example, the Taguchi robust design methodology (Taguchi and Clausing 1990;

Taguchi and Rafanelli 1994) assumes that product planning is not part of the systematic design process. However, nowadays it is generally acknowledged that not only the architect, but the representatives of all key life-cycle disciplines must be involved from the onset to ensure more reliable planning (analysis of requirements) of what needs to be delivered in the project (Fischer et al. 2017). The early stage of design differs from the traditional design process in that there is a lot less information available. Exploration through the interpretation of needs, ideas, and requirements is the primary driver, and iterations, involving the making and testing of assumptions, are required to develop design knowledge and discover how things could be. However, it is not just figuring out the problem and solution framing, but also the aligning of the different perspectives and expectations of all stakeholders (Halstrøm and Galle 2015; Koskela et al. 2018). Thus, the development of design management as a discipline must consider the very dynamic nature of the early stages of design, where traditional approaches fall short. New strategies, processes, methods, procedures, tools, and capabilities need to be developed to cope with the required iterations and align the social and technical dimensions of the early stages of design.

The period after the pre-design phase is the one that is typically considered the design process. As was seen in the second case study, the solution space is narrower than it is in the pre-design phase, and the focus is on the systematic study of alternatives. More precisely, the emphasis is on the causal analysis of the alternative embodiments of an artefact. However, this does not mean that there is no need for interpretation through the collective generation, development, and evaluation of alternatives. Both, the social and technical views of designing need to be addressed in design management.

Two more general implications can be drawn from the work in this dissertation. The first is related to the consideration of the final (objective) justification of designs (Galle 2008). In the design process, designers use models to make predications. But models are always simplifications of reality. Only when the designs have actually been produced or put into use can the decisions made in the design process be validated; i.e., users are or are not satisfied with the artefact. Thus, design managers should consider how to integrate feedback from building construction and operations back into the design, to facilitate the learning of designers.

Second, it was proposed in Chapter 5 that design should be conceptualized as a fractal embedded in the social and design processes and carried out at the individual level. More precisely, this means that the structure of design processes, being recursive in nature and path dependent, is self-similar across different scales. This has been already acknowledged in lean design management, where four levels of management (project, phase, week and day management) have been implemented (Ballard and Koskela 2009; Hamzeh et al. 2009). However, this connection between the recursive and path-dependent nature of the design process and design management requires further study before better methods and tools for managing the design process can be developed.

Finally, though design has been explored in the design management discipline, these investigations have not been exhaustive. For example, design management has yet to consider the human-centered design approach, in which a plethora of methodologies, methods, and tools to probe, engage, and facilitate communication with future users and stakeholders have been devised. The proposition that design management possesses a dual nature (subject and object-oriented activities) just as designing does can be taken as a starting point for the future development of the design management discipline. Design management is the management of the designer's structured system of the situated object (technical) and subject-oriented (social) mental and external activities. However, further analysis of the implications for design management is beyond the scope of this research and needs to be addressed in future studies.

7.4 Chapter Summary

In this chapter, the new design model, the main contribution, was compared with well-known documented contemporary design theories and models. This helped to validate the comprehensiveness of the new model. The fulfillment of industrial and academic success criteria through the primary outcomes of this thesis was also evaluated. The new model provides an improved understanding of the subject matter, and when operationalized in methods and tools, it has also been shown to improve the performance of building design practices.

The three main contributions articulated involved the synthesis of the interpretative and causal perspectives of designing, the intellectual history of the discipline of design, and the clarification of core terms, concepts of designing, and their relationships. The validity of the main outcomes was affirmed by contemporary conceptualizations of designing by Simon and Buchanan, corresponding features of the method of analysis and synthesis in contemporary design conceptualizations, empirical evidence from design case studies, and a comparison with contemporary design theories and models. Finally, implications for design management practice and research were articulated.

They who dream by day are cognizant of many things which escape those who dream only by night.

Edgar Allan Poe

8. Conclusions

This chapter first reviews the aim of this research and the questions considered and looks at how they were addressed. Next, the limitations of this research are addressed. Finally, recommendations for future research are made.

8.1 A Review of the Aim and Research Questions

The formulation of the research aim consisting of two parts was motivated by the identification of recurring problems in the delivery of building design projects. The main aim of this thesis is (1) to develop a comprehensive philosophical and conceptual framework as well as a design model integrating both technical and social phenomena; (2) and to use the resulting theory to develop better design and design management practices.

The aim was achieved by the devising of a comprehensive solution to the following three problems: the lack of proper philosophical framing, the lack of conceptual clarity in the definition of design, and unclear relationships between the design theory and theory-driven practices. The design research methodology was used and the solution was divided into two parts: a new design model embodying the explanations of interpretation and causality in the design process and the development of better practices for building design and design management. The new design model was developed on the basis of the ancient writings of Aristotle and contemporary philosophical and design literature. It was instantiated in practice through three case studies, which supported the refinement of the overall argument that theory-driven practices improve design and design management performance. The usefulness of the instantiations was evaluated quantitatively and qualitatively in the two case studies involving participatory action research and in one experimental case study.

The four research questions posed in Chapter 1 are revisited below. After each question, a short answer describing how it was addressed as the research evolved is provided.

1. **What are the key philosophical ideas relevant to the framing of design conceptualizations?**

In Chapter 3, an overview of the concepts of the philosophy of science relevant to design theorization was provided. The underlying commitments and assumptions deriving from metaphysics, ontology, epistemology, and inquiry determine the selection of the research paradigm and therefore, the focus of analysis, considered or disregarded features, and expected outcomes of the design research. This is made evident by the historical development of the productive sciences of engineering, design, and design management, which were influenced by the intellectual forces surrounding them, in addition to other factors. Historically, the three prevailing research paradigms that had an impact on the development of the productive sciences were positivism, constructivism, and pragmatism. Most design research has subscribed to either the positivist or constructivist research paradigm. However, it was argued that pragmatism is in fact more appropriate, for several reasons: Design is a processual phenomenon (a matter of process metaphysics rather than thing metaphysics), and design ontology relies on the categorization of fundamental human activities into the subject-oriented (sensory experience, perception, and conception) and object-oriented (deliberation and mental and external actions). Design epistemology is a concept that describes the relationship between theory and observation, the subjective and objectives claims of design knowledge. For design research, an activity-based epistemology that focuses on the study of both how things are and could be is more appropriate than a natural epistemology that focuses only on the study of how things are. There is a difference between the philosophical and mathematical notions of analysis and synthesis. In this research, analysis and synthesis were considered from the philosophical perspective. Analysis and synthesis are characterized as metaphysical and epistemological theories of human inquiry, representing methods of inquiry and processes of things. The results of the analysis of the philosophical framing was presented in sub-section 3.3.5.

2. **What are the fundamental concepts of the method of analysis and rhetoric in the ancient Greek context and in contemporary contexts?**

To justify the consideration of the method of analysis and rhetoric as the fundamental models for design model development, Chapter 4 addressed the requirements for the new design theory, drew a comparison with existing theories and approaches, and considered the essential concepts and principles of the method of analysis and rhetoric. The method of analysis and rhetoric can be considered design theories because they describe the strategies of inquiry for the conception of geometric figures and the making of persuasive speeches, respectively. The two strategies are concerned with two distinct problems, causality and interpretation, respectively. Designing does not involve solely either the problem of causality or the problem of interpretation. In the different stages of design process, the problems and solutions of design and designing contain varying proportions of both interpretation and causality. Thus, the two strategies may be considered complementary and need to be synthesized for a more comprehensive conceptualization of designing. Furthermore, both strategies of inquiry have analogous features in existing design theories. These two strategies explicitly define the objects and processes of human problem-solving and argumentative inquiry; in modern terms, these include the contexts of design, stages/phases, iterations, the causal structure of transformations, and the modes and types of mental and external activities.

3. **What kind of new design model can be constructed based on the two strategies of inquiry?**
   In Chapter 5, the new design model was constructed by synthesizing the philosophical concepts and the two ancient strategies of inquiry. The new model embodies the relationships between fundamental human subject- and object-oriented activities, contexts of design, design stages/phases, types of iterations, the causal chain of transformations, and types of mental and external activities. As a whole, it represents the design process structure, the strategic sequence that aligns the two different perspectives of interpretation and causality. Design is a progression from the rhetorical perspective, where needs, goals, uses, and requirements are interpreted, to the method of analysis perspective, where the causal structure is designed and the artefact is made, and then back to the rhetorical perspective, where designs are delivered and justified and then undergo evaluation by users. The proposed new design model is more comprehensive than the ones it was compared with. Although these contain aspects not present in the new model, like the axioms of axiomatic design or the formalism of the C-K theory, these aspects are not at the same level of generality as required by the new model. In this research, the unification approach to theory development was taken. Thus, the focus was on breadth over depth.
4. **How will the methods developed based on the new model benefit the practices of design and design management?**
   To answer this question, three practical interventions were carried out through case studies. The results of these studies are reported in Chapter 6. In the first case study, the early stages of the design process were addressed with a particular focus on the invention and evaluation of ideas, issues, and requirements, on the basis of the given problematic situation and a study of potential users and their needs. This corresponds to the conception quadrant of the new model proposed in **Figure 17**, where the development and construction of the new model was primarily informed by the rhetorical strategy of inquiry. The design process structure became the basis for the development of a shared framework for designing, making it possible to align the efforts of different disciplines. The outcome of the design process was an innovative warehouse building concept which the client was satisfied with. The concept was validated on the market using a fictive marketing campaign. In the second case study, the steps of the new design model were aligned with three

different methods: integral morphological C-K theory, Taguchi robust engineering, and building information modelling. The alignment was used to develop a better energy and cost efficient design concept. This is significant, as the failure to meet specified performance criteria has become almost a commonplace in the energy efficient design of buildings. In comparison to the results reported in the original study by Pikas et al. (2015), the results achieved here were significantly better, showing a reduced level of energy consumption and lower noise sensitivity. In the third case study, the usefulness of practical interventions based on the new model was evaluated in a design management context. With a view to the improvement of practices, participatory action research was carried out. The research resulted in significant improvements in the design organization. Thus, in all cases, improved performance was demonstrated.

8.2 Limitations

Some of the limitations of this research were addressed earlier in Chapters 6 and 7, i.e., the fact that the concepts are not directly justifiable and that evaluation was limited to that provided by the three case studies. There are other limitations to be addressed below. These other limitations also suggest potential future design research directions.

First, the scope of this study was limited to the domain of building design and building design management, which might limit the generalizability of this research. However, as the focus here was on addressing the most fundamental concepts and aspects of human inquiry (Chapter 3) and of designing (Chapters 4 and 5), the new design model and the accompanying explanations are also relevant to other productive contexts, e.g., software engineering, mechanical engineering, and new product development. Also, given the author's background knowledge in construction and limitations on the length of this thesis, among other practical considerations, the evaluation had to be confined to the construction industry. Nevertheless, the general theory in Chapters 3 and 4 was informed by studies in other domains, and this should help to offset this limitation.

Second, in Chapter 3, only three different research paradigms, positivism, constructivism, and pragmatism, were addressed. However, several other potentially relevant research paradigms have been developed, including the phenomenology of lived human experiences (meaning-making) (Smith 2018) and the post-positivism of human conjecture (research as problem-solving) (Creswell 2013; Deutsch 2011; Popper 2014). However, due to the understandable limitations of time and space, they were omitted.

Third, design was conceptualized as part of the phenomenon of production. This is a common approach taken by design researchers (Buchanan 2009; Koskela 2000). However, the implications of considering design in the production context were only partially addressed in sub-sections 1.1.2, 2.2.1, 4.1.2 and 7.3.3. As argued by Ballard and Koskela (2009), the flow perspective is important in design, as designing takes place in a broader context and always involves related activities.

Fourth, although in parts of this study, aspects related to human cognition were addressed (e.g., see sub-section 5.4.4 and Appendix 3), the underlying mechanisms of human reasoning and behavior based on cognitive science and neuroscience were not extensively analyzed. However, according to Hay et al. (2017), basing design theorization on cognitive science could potentially help to reduce fragmentation and clarify basic design concepts and terms. Indeed, based on the author's own experience, the high level of design research fragmentation and the multiplicity of often overlapping concepts is making the design discipline difficult to study for newcomers.

Fifth, in sub-section 4.1.4, core concepts and definitions were proposed (design, designing, designer, design process, and social process) but not addressed in depth. With some deviation from the ideas of Love (2003), a model indicating the relationships between the core concepts was also proposed, but these relationships were also not addressed in depth. This shortcoming can be attributed to the fact that the focus here was on conceptualizing the design process and its structure.

Finally, in the third case study and sub-section 7.3.3, aspects related to design management and the implications of the new design model for design management were not fully explored. The treatment hardly does justice to the importance of the field of design management, especially considering the assumption that design management is influenced by how the design is conceptualized, observed in author's other work (Pikas et al. 2015; Pikas et al. 2015).

8.3 Recommendations for Future Research

In this research, designing was investigated in the context of building design and building design management. As the field of design research is vast, there are a significant number of research opportunities yet to be explored, not limited to the following:

- As is quite common in design research, the new design model can be further developed and refined through further research, especially regarding the identification of commonalities with existing theories and models and the analysis of how they would benefit (from) the proposed new model. For example, Gero has over time further developed and refined the FBS model (Gero 1990; Gero and Kannengiesser 2004; Gero and Kannengiesser 2007).
- The new design model is a generic representation of relationships among basic concepts of designing. With a view to further validation of the model, it could be applied in other productive application areas and determined whether it would help improve practices.
- Studying and analyzing the concepts of the philosophy of science could help make the underlying assumptions of design research more explicit. The potential to improve design research based on concepts from the

philosophy of science concepts has already been recognized in the design research domain (Crilly 2010; Dalsgaard 2014; Galle 2008; Love 2000).

- More in-depth analysis of designing in the context of the productive sciences should help clarify the relationships between different productive goals (delivery of the artefact, performance of the process, and customer value), the causal structure uniting goals and human action, and the management of these actions. Some research in this area has already been conducted by Koskela (2000).
- Over the last three decades, the cognitive sciences and neurosciences have made great strides. There is significant potential to clarify many aspects of designing based on new findings (Hay et al. 2017). A better understanding of human psychology can help better understand designing and the management of these processes (e.g., visual management and situational awareness).
- A specific related area of potential investigation is human intuition and insight, which refer to sub-conscious or unconscious processes of reasoning. Over the last three decades, the study of intuition and insight has expanded in the cognitive sciences (Bowers et al. 1990; Zander et al. 2016), management sciences (Sadler-Smith 2008), and human expertise studies (Claxton 2000), but is yet to be fully explored in the design context (Badke-Schaub and Eris 2013; Durling 1999).
- In section 4.1.4, the core concepts of design were defined, and a preliminary proposal of the relationships between core concepts was made. However, this requires further study and analysis. For example, the development of a better understanding of 'designing with humans' would benefit the design domain.
- The aspects of design management and the implications for design management of the new understanding of designing need to be further explored. A more profound understanding of designing should benefit design management, but this requires further research and developments.
- Finally, this research is not and cannot be exhaustive regarding the ancient strategies of inquiry. There is a growing body of knowledge related to these underlying methods of inquiry, especially rhetoric (Halstrøm 2017). Thus, further research on these methods of inquiry could potentially reveal new aspects and dimensions; e.g., Aristotle's "elements of circumstances" in rhetoric deserve closer study (Giacomin 2014).

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Appendix I: Examples of the Use of the Method of Analysis

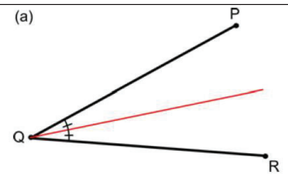
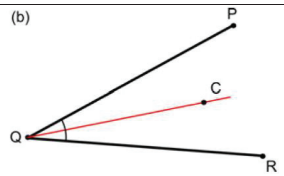
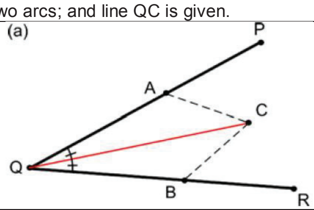
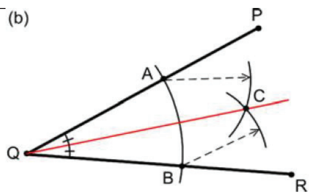
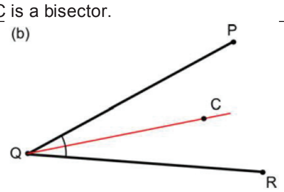
Example: Comparison of Theoretical and Problematic Analysis

In **Table 1**, a problematic analysis is juxtaposed with a theoretical analysis, both based on the same construct from Euclidean plane geometry. This example, also referenced by Kroll and Koskela (2015), involves the classical method of constructing figures with only a compass and an unmarked straightedge. In this work, the framework proposed by Hintikka and Remes (1974), consisting of three stages and sub-stages, is used to illustrate the two kinds of geometrical problem-solving.

According to Pappus (Heath 1956), one starts by assuming the thing sought to be known or true and working backward through the chain of ends-means relationships until arriving at something known to be possible/impossible or true/false, respectively. This is called analysis. When one arrives at something possible or true, then the solution itself (construction or proof, respectively) is carried out in the synthesis. However, if one arrives at something impossible/false, then the thing sought must be impossible/false too; i.e., there is no solution. In Polya's terminology, analysis is the devising of a plan of action to arrive at a desired end, while synthesis is the actual implementation of the plan (Polya 2014).

Kroll and Koskela (2015), who leaned towards the directional view of the method of analysis, focused on types of reasoning. Therefore, other aspects, such as the structure of the method of analysis, received little attention. For example, according to Heath (1956) and Hintikka and Remes (1974), the thing sought (enunciation) consists of something 'given' and something 'sought', and both are not always are given. Sometimes only one or the other is given, and the other needs to be derived. Polya's first stage 'understand the problem' illustrates this well, and he has listed several useful recommendations on how to carry out this stage (Polya 2014).

Table 1. Juxtaposition of problematic and theoretical analyses, adapted from Kroll and Koskela (2015), presented in the configurational framework of the method of analysis.

	Problematic Analysis	**Theoretical Analysis**
I Enunciation		
I(a) – Given (*dedomena and data*)	An angle ∡PQR.	An angle ∡PQR and an interior point C at equal distance from the legs are given.
I(b) – Sought (*zetoumenon*)	Find/Construct its bisector.	Prove that QC is a bisector of PQR.
II Analysis		
Illustration		
II(a) Analysis proper	*Let it be done.* Let a line from Q to some interior point C be drawn; QC is the bisector of ∡PQR; hence ∡PQC=∡RQC; and PQC and RQC are congruent triangles; hence QC is a common side; the other sides, which we call QA and QB are built on the original angle's legs; QA=QB.	*Let it be done.* Assume that QC is indeed the bisector of ∡PQR; hence ∡PQC=∡RQC; and PQC and RQC are congruent triangles; hence QC as a common side; the other sides, which we call QA and QB, are built on the original angle's legs; where CA and CB are perpendiculars from C to PQ and RQ, respectively; hence from congruency, CA=CB.
II(b) The 'resolution':	But the ∡PQR is given in I(a); hence QA and QB are given [constructing lines of equal length is known to be possible using a compass and an unmarked straightedge]; points A and B at an arbitrary distance from C are given; hence C with equal arcs from A and B is given at the crossing of two arcs; and line QC is given.	But this is already known in the problem: it is given in the problem that point C is at an equal distance from the given legs.
Illustration		
III Synthesis		
III(a) Construction	Let the angle be ∡PQR; we draw an arc from Q with arbitrary length that crosses its legs at A and B; we make QA=QB; we draw two equal arcs from A and B and call their crossing C; we make AC=BC; a line from Q to C will solve the problem	Draw from the given point C perpendiculars to PQ and RQ
III(b) *Apodeixis* of the synthesis (proof)	Because ∡AQC=∡BQC is congruent with/identical to ∡PQC=∡RQC, QC is the given bisector.	Because CA=CB, it follows that ΔQAC≅ ΔBQC by LH (hypotenuse leg of a triangle). It follows that ∡AQC=∡BQC, and so QC is a bisector.
Illustration		

Example: Problematic Analysis adapted from Hintikka and Remes

The aim of this example is to illustrate the function of 'resolutions', which establish the independence of all geometrical entities required in constructions. The 'analysis proper' is heuristic in nature, but not the 'resolution'. In the resolution, no new objects or relationships are introduced; rather, the ones given or implied are justified. It is the finding of the right constructions that is heuristically crucial in the method of analysis (Hintikka and Remes 1974). This examples follows the general outline of the configurational view of analysis, with the exception of the conclusion.

I Enunciation: (a) That which is given (the dedomena)

Let a segment of a circle be given, with chord AB. Let a ratio be given (**Figure 1**). Inflect...

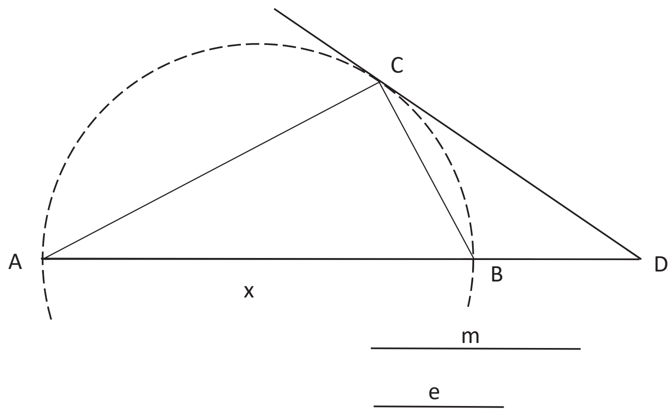


Figure 1. The dedomena, as provided in Hintikka and Remes (1974).

I Enunciation: (b) The thing sought (the zetoumenon)

... two line segments from A and B to C, in the given ratio.

II Analysis: (a) Analysis proper

Let it be done.

Let a tangent CD from C be drawn;

$AC_2:CB_2=AD:DB$.

II Analysis: (b) The 'resolution'

But AC:CB is the given ratio in I(a); hence $AC_2:CB_2$ is given; hence the ratio AD:DB is given. And the points A and B are given; hence the point D is given, and the tangent DC is given; hence the point C is given.

III Synthesis: (a) Construction of the synthesis:

Let the segment be ABC, and the ratio e:m. We make $AD:DB=e_2:m_2$. We draw through D the tangent DC; the straight lines AC and CB solve the problem.

III Synthesis: (b) *Apodeixis* of the synthesis (proof)

Because e_2:m_2=AD:DB, and AD:DB=AC_2:CB_2 (CD is a tangent by construction - cf. III(a)), e_2:m_2=AC_2:CB_2; hence e:m=AC:CB; thus the lines AC and CB solve the problem.

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Appendix II: Analogous Features in Current Design Theories

1. STARTING AND END POINTS

Method of Analysis: In the method of analysis, the start and end points are considered qualitatively different. In geometry, it is assumed that problems are given or can be objectively defined. The end of analysis is something admitted, already known, or if the geometrical problem is partially or wholly underspecified, it leads to something impossible. Synthesis begins after analysis and demonstrates or proves that the 'thing sought' exists. The start and end points of analysis and synthesis represent the different states of design knowledge.

In current design literature, various counterparts to the abovementioned aspects of the method of analysis can be found. Design projects have been associated with two different types of objectives, 'compliance to requirements' and 'fit for purpose' (Oakland and Marosszeky 2017). 'Compliance to requirements' resonates with the method of analysis and has two faces. On the one hand, it is a specification of the thing sought, what is given and not given, while on the other hand, it is a process for ensuring that the specifications have been met. This is known as verification and defined as follows (Forsberg et al. 2005): "Proof of compliance with specifications. Verification may be determined by test, inspection, demonstration, or analysis. [...] Was the solution built right?"

The objective of the specification is to narrow the solution space; i.e., the state space for possible design solutions (Gero 1990). Several terms with more or less overlapping meaning have been used to describe the concepts related to the narrowing of the design space, such as requirements, objectives, performance criteria, and constraints. Nair et al. (2011) divided the narrowing concepts into two: requirements and constraints. Requirements are a set of statements of objectives and functions which the design must achieve or fulfill (Cross 2008). Requirements are assumed to be defined objectively and in solution neutral form (Stumpf and McDonnell 2002). Nair et al. (2011) defined design constraints as "relationships between design variables that restrict the range of possible values or a physical limit of one variable". Constraints can be absolute or flexible, and they are one of the following types: time, financial, process, standardization, and dimensional.

Design problems can be under-specified or vague or may not even be subject to systematization due to lack of information; this regards three aspects of the design problem (Restrepo and Christiaans 2004): start state, goal state, and the transformation function from start state to the end state. Simon (1981) described these as 'ill-structured' ('ill-defined') problems: problems whose structure lacks definition in some respect and cannot be solved linearly. The implication is that though problem structuring occurs mainly at the beginning of the design process, it also reoccurs during the design process (Restrepo and Christiaans 2004).

The descriptive C-K (Concept-Knowledge) theory has been proposed to provide a formalism for modelling the different logical states of design knowledge

– true or false (Le Masson et al. 2017). Therefore, in this respect there is a remarkable similarity to the method of analysis.

Rhetoric: The starting point is the problematic situation (time, place, subject, common ground, and audiences), and the end is concerned with whether the audience was persuaded.

Harfield (2007) distinguished between 'the-problem-as-given' and 'the-problem-as-taken’. The problem with the 'problem-as-given' view lies in the underlying assumption that problems of design are 'out-in-the-world-to-be-captured' and not influenced by the personal preferences and desires of the designer. Thus, the limitation of the rational definition of design problems is that it has neglected the active agenda shaped by the experiences, values, and goals of different stakeholders, focusing on the passive agenda arising from its organization and representation (Lloyd and Scott 1994). In 'the-problem-as-taken’ view, designers have a more active role (Harfield 2007): "...architects construct the problems they seek to solve while at the same time defining and limiting the solution possibilities available to them".

'Fit for purpose' is a measure of how well the artefact helps to achieve customer purposes (Whelton and Ballard 2002), i.e., it starts and ends with the customer. This view is primarily concerned with the effects that the designs will have on its environment (society, the owner, and (potential) users) (Fischer et al., 2017, Goldhagen 2017). The process of establishing customer satisfaction is known as validation (Forsberg et al. 2005): “Proof that a developed system meets actual user needs and that the user is satisfied. [...] Was the right solution built?” Jensen (2011) and Emmitt and Ruikar (2013) developed a dynamic briefing method for continued customer/user involvement in understanding the design situation, needs, and requirements. The same briefing sessions were used to evaluate the proposed designs.

In the argumentative view, design requirements and constraints are not assumed to be objectively given but need to be discovered through a continuous process of framing and re-framing the design situation (Halstrøm 2016). It is not just a matter of specifying requirements and constraints, but there is also the continuous, cyclic, and dynamic process of evaluating and re-evaluating the situation from different perspectives.

There is another way to conceptualize the start and end points of the design process. Lurås (2016) proposed a systemic model of the design situation that he described as a “system of systems”, borrowing from systems theory (see **Figure 1**). The three systems consist of the ‘system we design within’, the ‘system we design for’, and the ‘system of design’. The ‘system we design within’ can be considered the highest level of the design situation, the context in which, according to software engineering, the business and needs are analyzed (Sutherland 2014). Altschuld and Witkin (2000) defined “need” as “a measurable discrepancy between the current and desired status for an entity”. The system’s overall goal (purpose) is defined in this context. The ‘system we design for’ (the transactional environment of the artefact) is the study and analysis of immediate users and their needs and goals, resulting in a description of a set of use functions and properties (Andreasen et al. 2014). The 'system of design' is the description of how the artefact fulfills the function that is necessary to meet its purpose (Vermaas 2013). It could be argued that the starting and end points in the method of analysis conceptualization of design are at the boundary of 'system of design', the functional, configurational specification of the artefact in the analysis, and the construction of that design and its testing to determine whether it meets the functional requirements in the synthesis. Design rhetoric starts in the 'system we design within', moves through the 'system we design for' and to the 'system of design', and returns to the 'system we design within'. That could also be considered the basis for distinguishing between the process of verification (whether the artefact meets functional and performance requirements) and the process of validation (whether the artefact meets the needs of users).

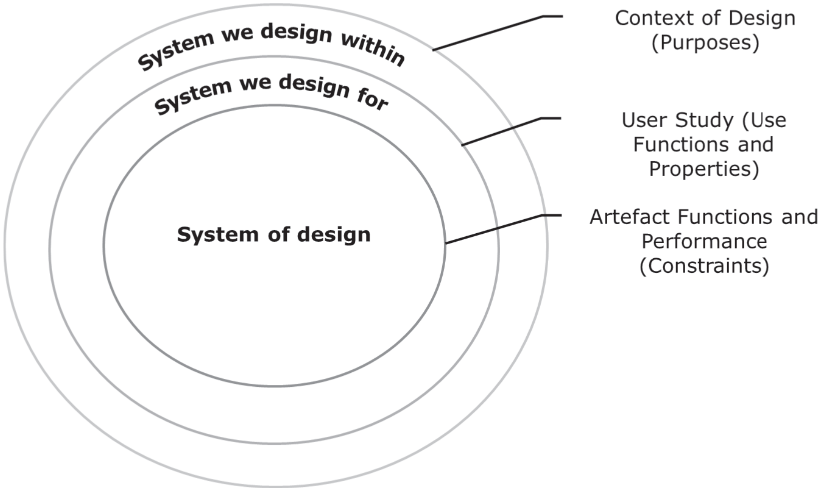

Figure 1. Design situation framing using the "system of systems" concept (adapted from Lurås (2016)).

2. TYPES OF ANALYSIS

Method of Analysis: In the method of analysis, two different types of analysis been defined, the problematical and theoretical. They are not incompatible, but rather complementary modes of solving geometric problems. Polya (2014) proposed a different interpretation of the types of analysis: problem-solvers tend to use a problem or solution-oriented strategy, depending on the problem given and the experiences and skills of the problem-solver.

The first interpretation corresponds to the invention or selection of a solution principle from among different alternatives and translating the design principle into a practical solution (structure). Several concepts and methods that address these two steps have been proposed. For example, on the macro-level, the domain theory based approach proposed by Andreasen et al. (2015) or engineering systems approach by Ullman (2009) divide the design process into conceptual design and design embodiment stages. On the micro-level, the design conceptualization proposed by Gero and Kannengiesser (2004) assumes a progression from function to behavior and structure.

Based on the Polya's (2014) interpretation, Koskela et al. (2014) proposed another interpretation: designers use problem or solution-oriented strategies. In the context of novice and expert designers, this means that novices have a solution to find, while experts have a theorem to prove (Ahmed et al., 2003). Lloyd and Scott (1994) argued that personal values, beliefs, and experiences are the factors that influence a designer's choice of a problem- or solution-oriented approach; i.e., whether a designer focuses on describing abstract relations and concepts (problem-oriented) or descriptions of possible solutions (solution-oriented) (Restrepo and Christiaans 2004). Of course, this does not mean that novice designers do not do synthesis or that expert designers do not do analysis. Instead, the question is about what the dominant strategy is.

In a recent cognition study on the mental stages of mathematical problem-solving, four distinct stages were identified: encoding (interpretation), planning, solving, and responding (Anderson et al. 2016). According to this study, the duration of the planning stage increased when the method of solving the mathematical problem became less obvious. The duration of the solving-stage increased when the number of steps to produce the solution increased. The duration of the responding stage increased according to the difficulty of the motor actions required to produce the answer (Anderson et al. 2016). Although this study did not consider proficiency as a factor in the solving of mathematical problems, the four stages with varying duration were evident in all types of problems. This implies that the four stages have complementary functions, as analysis and synthesis in the method of analysis.

However, in the design literature, there seems to be a continued attempt to assign novice and expert designers to problem- and solution-oriented approaches, respectively (Restrepo and Christiaans 2004). The confusion seems to arise from the confounding of the different levels of abstraction. On a macro-level (e.g., as an organizational design process) and meso-level (e.g., as a problem-solving process), a design might look like a progression from the problem analysis to the solution synthesis and evaluation. On a micro-level, the structuring of the design problem does not occur in isolation from possible design solutions, as demonstrated by a parameter analysis (Kroll and Koskela 2015), or as argued by Cross (2008).

Rhetoric: In rhetoric, there is no corresponding concept. Instead, the focus is on the entire communication aimed at persuading the audience or achieving adherence to one's ideas.

In rhetorically oriented design, problems are characterized as being 'wicked' or 'tamed' (Rittel and Webber 1973, Buchanan 1992). Rittel and Webber (1973) defined wicked problems as a "class of social system problems which are ill-formulated, where the information is confusing, and where the ramifications in the whole system are thoroughly confusing". Wicked problems have the following characteristics (Rittel and Webber 1973): a definitive formulation of the problem is lacking; there is no stopping rule; solutions are not true or false, but bad or good; an exhaustive list of admissible operations is lacking; for every problem there are many explanations, depending on the designer's experience and knowledge; every wicked problem is a symptom of another; there is no definitive test; every problem is unique; and there is no room for failure. There is inherent indeterminacy in the design process (Buchanan 1992). Thus, in this formulation, the problem, solution, and audience spaces are co-developed (Halstrøm and Galle 2015).

3. STAGES

Method of Analysis: In the method of analysis, the analysis includes three stages: clarification of the problem, the analysis proper, and the resolution. Synthesis consists of three mirroring stages: construction, demonstration/proof, and the conclusion.

First, it must be noted that design processes can be described at different levels of detail: in terms of product life-cycle models (at the organizational level); in terms of individual or collective problem-solving cycles; and in terms of individual mental and practical actions and operations. For example, the approach based on structural activity theory (Bedny and Harris 2005) developed by Cash et al. (2015) attempts to develop a multi-scale conceptualization of design activity.

The three stages in the analysis are analogues to the specification of requirements (functions and constraints), the finding of a solution principle in the conceptual design stage, and the embodiment of designs utilizing the solution principle (Roozenburg and Eekels 1995). Though there were some significant differences, similar stages across different industries were reported by Gericke and Blessing (2012).

The stages in synthesis, on the macro-level, correspond to the fabrication/installation of components to form assemblies, the formation of systems from assemblies, and finally testing (also known as commissioning) the systems to ensure a well-functioning building system, its delivery, operation, and remodelling/demolition (Reed 2009). At the micro-level, in addition to objective actions and operations (making, constructing, and testing), design also involves subjective actions and operations: assembly, deduction, and induction (Kroll and Koskela 2015).

Rhetoric: Rhetoric consists of the following stages: invention, arrangement, style (implementation), memory, and delivery/judgment.

In the context of design rhetoric, the model proposed by Brown (2008) is an example of the rhetorical design process; it has three steps, inspiration, ideation, and implementation, or alternatively, five steps, empathizing, defining, ideation, prototyping, and testing. However, Buchanan's proposal of a set of "fundamental arts of design thinking" for synthesizing appeals, form, and medium (Buchanan 2001) is more directly related to rhetoric:

- […] the conception or invention of new products and their discussions have yielded a rich variety of common and proper places that they employ in generating possible innovations;

- […] judgment, which means selecting among possible inventions or product concepts those that are potentially viable as constructs in particular circumstances and under given conditions. The problem of selection and judgment is properly a preliminary form of decision making […]
- […] how a product concept is developed and tested […] central themes of design thinking receive their full exploration in concrete prototypes that express the useful, usable and desirable. […] this is the area of arrangement and disposition.
- […] designers are concerned with evaluating the objective worth of products. The criteria for evaluating products – and determining whether they should be carried forward in production and distribution – come from many sources. They come from the personal values of the designer, the interests of the manufacturer and client, the needs and desires of individual communities of use, and society at large. […] we must ask who is the proper judge of the value or worth of a product as it is being developed and after it has been produced.
- […] the fifth art of design, concerned with expression or style. Visualization is an artful consideration at each stage of the four primary arts of design thinking. Sketches, diagrams, and preliminary prototypes are all conceived with persuasive intent, and a rhetorical study of this aspect of design reveals how expression and delivery – as well as memory – are woven together in design practice. […] arguments at each stage of conception, planning and realization must be presented in a compelling manner. […] the arts of design are not simply procedural steps […] They form a sequence of considerations, but the considerations are integral and sometimes simultaneous in practice.

When these arts of design are compared to the original canons of rhetorical discourse, at first sight there seem to be significant differences. For example, Buchanan (2001) has merged the style, memorization, and delivery stages. The merging of memorization with style is sensible in the context of design, as the memorization of a speech is specific to oral persuasion. Memory in the context of design takes the form of representations, such as sketches, digital building models, and specifications (Eastman et al. 2011).

Style, or in modern terms, implementation or communication, is also where there is an essential difference between the method of analysis and rhetoric. In the method of analysis, the implementation of simple elements, such as points, lines or planes, is considered unproblematic, as the methods for constructing these simple elements are well-established. In rhetoric, implementation plays an important role in effort to influence the audience. This stage connects analysis and synthesis; i.e., the chosen design solution is communicated/transmitted to the tangible medium (Fujimoto and Miller 2007). This is also important in the design of buildings, as the fabrication or construction of parts is subject to consideration of consequential parameters and tolerances stemming from the methods of implementation (Fischer et al. 2017, Reed 2009). This is due to the fact that physical operations are intrinsically subject to variation (Taguchi and Clausing 1990, Taguchi and Rafanelli 1994), in contrast to the world of ideas.

However, the merging of delivery with the style and memory stages does not seem to be justified, especially in the context of the entire life-cycle of construction projects. For example, there are deliveries throughout the entire life-cycle of a building project, during the different stages of design, and ending with the delivery of the actual building when construction is complete (Fischer et al. 2017). The phased delivery of partial solutions of a building design is expected to help align the different views of stakeholders; this is indeed a fundamental tenet of stage-gate process models (Wynn 2007).

4. MODES AND TYPES OF MENTAL AND EXTERNAL ACTIVITIES

Method of Analysis: The method of analysis represents the model for necessary reasoning. The types of reasoning involved in analysis are transformation, regression, and decomposition; in synthesis, composition, deduction, and induction. Synthesis has a dual nature and also involves objective operations: assembly (construction), testing, and verification.

Design reasoning has been considered a prototypical case of human intelligence and cognition (Restrepo and Christiaans 2004): "design requires devising future states of the world (goals), recognizing current ones (initial states) and finding paths to bridge both (transformation functions)". The importance of design reasoning was stated by Rittel (1987), who said that "studying the reasoning of designers becomes a way of attempting to understand how design happens – possible the only way".

Formal studies of design reasoning are either logical or psychological, focused on form and rules or content, and are approached from the perspective of an individual designer (Cramer-Petersen and Ahmed-Kristensen 2016).

Since C. S. Peirce, the logical types of reasoning have been divided into deductive, abductive, and inductive inferences (Niiniluoto 1999). Many design models have combined the three types of inferences into a three-stage process of problem-solving inquiry 'analysis-synthesis-evaluation' (Cramer-Petersen and Ahmed-Kristensen 2016, Jones 1992, Cross 2008, Roozenburg and Eekels 1995).

The creative nature of design reasoning has been related to abductive inference (Roozenburg 1993, Kroll and Koskela 2014, Kroll and Koskela 2016), as it is the only method of inference that introduces new ideas. Jones (1992) described this as a 'leap of faith'. The are two commonly held views on abduction in design (Dong et al. 2015). One holds that abduction is the synthesis of complex and contradictory information, and the other, that abduction is a two-step process, reasoning from function to solution principle and from solution principle to structure. The latter is what corresponds to two-step innovative abductive reasoning (Kroll and Koskela 2016).

There is also a third interpretation of abduction. Koskela et al. (2018) argued that abduction is instead a property of inference types and defined a total of eight types of abductive inferences (Koskela et al. 2018). Here they have been organized into two categories: analysis involves strategic abduction, abductive invention of requirements, abductive transformation, abductive regression, and abductive decomposition, while synthesis involves manipulative abduction, abductive composition, and abductive analogical reasoning. Therefore, abduction can occur at any stage or step of the design process.

As is evident from the eight types of abductive inferences, designers also use other types of inferences. In the proto-theory of design, the following have also been defined: transformation, regression, and decomposition in the analysis and deduction, composition, and induction (not explicitly defined) in the synthesis (Kroll and Koskela 2015).

Unlike rule-based theories of reasoning, the cognitive theory of reasoning suggests that human reason makes use of mental models based on perception, imagination, and the compression of discourse (Johnson-Laird 2006). The mental model theory (Johnson-Laird 2006) suggests that humans infer through possibilities and test the validity of an idea by using experience to simulate the world. Mental models represent a structurally similar reality; i.e., they are iconic. The validity of the inference must hold for all models of the premises to be accepted. To simplify reasoning, humans focus on a subset of the possible models of multiple-model problems. For example, as suggested by Kroll and Koskela (2015), in parameter analysis it is argued that the designer focuses on a single design parameter at any given time in the design process.

In addition to intra-mental reasoning, the problem solving of geometers also involved extra-mental actions and operations. These two are the interactive strategies of inquiry, operating in and on the world. Tversky (2011) argued that when problems overwhelm the mind, they are put into the world, and she called these interconnections “spractions”.

Rhetoric: In rhetoric, the mode is known as plausible argumentation, and the reasoning used in a logical appeal is inductive or deductive, focused on the particular or probable. Despite the fact that no direct support was found in the literature, it seems probable that reasoning may also be abductive. Operations in rhetoric include style (implementation) and delivery.

Since Rittel and Webber (1973) argued that design problems are wicked, design scholars have become interested in studying argumentation as a form of design discourse (Buchanan 1985). In argumentative conceptualizations of design, the task of a designer involves the values and purposes embodied in the context and its circumstances (Stumpf and McDonnell 2002). The assumption is that the discourses of an individual designer or design team have similarities to the reasoning types in their verbal disposition - what they say and do (Cramer-Petersen and Ahmed-Kristensen 2016), including induction and deduction (also possibly abduction). This is the underlying assumption in protocol studies (Hay et al. 2017).

Cramer-Petersen and Ahmed-Kristensen (2016) argued that whether designers work alone or in groups, design involves issues and contradictory positions that are open and mutually dependent on each other. During the design process, these perspectives appear as speculation, argumentation, trade-offs, and negotiation.

In the context of argumentative conceptualizations of design, the framing and reframing of problems have been considered particularly useful. The idea of framing, initially proposed by Schön (1984), appeals to the notion that the subject matter of designers exists in the problems and issues of specific circumstances (Buchanan 1992). It stresses the dynamic, cyclic, and unfolding nature of design discourse. Designers need to frame themes of the desired value to conceive solutions.

5. THE UNITY OF THE TWO DIRECTIONS

Method of Analysis: Analytic and synthetic inquiries have complementary functions. The former is focused on establishing the necessary conditions for solving the problem, and the latter is concerned with the demonstration and proof of theorems and problems. In the method of analysis, the stages of analysis and synthesis mirror each other: enunciation-conclusion, discovery-proof, and resolution-construction.

The 'V-model' proposed by Forsberg et al. (2005) assumes the unity of the two directions. The V-model is a representation of system evolution from the perspective of decomposition and definition in the analysis and integration and verification in the synthesis, i.e., activities on the left and right legs of the V-model, respectively (Forsberg et al. 2005). The definition of requirements and solutions in the left leg are the basis for planning the verification and validation methods implemented in the right leg after the integration of parts into assemblies, assemblies into sub-systems, and these sub-systems into the complete system.

Rhetoric: In rhetoric, it is assumed that the problem, solution, and audience spaces are developed in parallel.

In design rhetoric, as argued by Buchanan (2001), invention evolves in parallel with judgment, and arrangement in parallel with evaluation. Another example of the unity of analysis and synthesis can be found in the model proposed by Cross (2008), where problems and solutions are assumed to evolve simultaneously. In this sense, it is argued here, that the stages in the left leg of the V-model involve smaller nested V-models. This is evident in the dual V-model, where the system architecture and entities co-evolve (Forsberg et al. 2005).

6. PERSUASIVE STRATEGIES (APPEALS)

Method of Analysis and Rhetoric: In the method of analysis, the argument or discourse is subject to necessary technical reasoning. In rhetoric, the argument or discourse is subject to all three appeals, the interrelated qualities of useful (*logos*), desirable (*ethos*) and usable (*pathos*) (Buchanan 1985).

Useful is the primary concern in technical design, while in design rhetoric designers must skillfully blend the useful, desirable, and usable in the design argument (artefact) to realize their ideas. For example, Goldhagen (2017) argued that the built environment shapes human cognition, behavior, and well-being. Designed artefacts are not passive objects but form an active part of human existence. Thus, as conceptualized by Buchanan (1985), the designer is not creating an object or thing but developing a persuasive argument to influence an audience.

The difference between the approaches of the method of analysis and rhetoric is also evident in the different conceptualizations of 'function'. The two different approaches could be described, according to Vermaas and Dorst (2007), as the structural and intentional conceptualizations of design, respectively.

According to Erden et al. (2008) and Chen et al. (2015), design inquiry is about the transformation from subjective to objective reality, from subjective needs to an objective description of structures for production and use. The objective realm is outside of the designer, composed of things and events, while the subjective realm is the mental world of the designer(s), setting expectations and interpreting the design context and results.

Moreover, according to Erden et al. (2008), although no unified definition of a function exists, a function bridges the subjective and objective realms. It is the designer's interpretation of what the artefact should do or how it should work. Erden et al. (2008) and Vermaas (2013) proposed three principal categories of coexisting meanings of function: "function as the intended behavior of devices, function as the desired effects of the behavior of devices, and function as the purpose for which devices are designed".

According to the first view, function refers to the operation of an artefact, device, or system. A system is described through black-box modules connected by input-output relations according to the "device-centric ontology" (Erden et al. 2008). In device-centric ontology, the function is realized through the internal parameters of an artefact. Andreasen et al. (2015) referred to them as characteristics, a class of properties of an object that define how the object's behavioral properties are realized. Generally, this means the internal configuration and structure of the artefact.

The second conception of function is concerned with the effects that the operation and behavior of a system have on its environment. Erden et al. (2008) described this as a processual view of function, where the focus is on user processes connected with the artefact rather than on its components. According to the environment-centric ontology, the intentions of users are linked to objects via the realm of functions (Erden et al. 2008). The object is deployed in the "world" in a particular manner (given a mode of use), realizing some role in it (Vermaas 2013).

The third conception of function is the teleological view of function (Erden et al. 2008): it is concerned with the purpose of the artefact. In the teleological view of function, priority is given to the needs of organizations and users, and function as an effect is achieved as a result of the combination of the function in device-centric terms with the 'mode of deployment' of the object (Erden et al. 2008). This means that the design process is a functional modelling of what the device and its components do or what the purpose of the device and its components are in terms of human needs.

The device-centric view of function corresponds principally to considerations in the method of analysis, while the processual and teleological views of function correspond principally to considerations in design rhetoric. In other words, the focus is either on the object-oriented or subject-oriented conceptualizations of design, or as Bucciarelli (1994) described them, the object and subject worlds of engineering design.

7. STRATEGIES OF REASONING

Method of Analysis and Rhetoric: Analysis in the method of analysis can be logical or heuristic. Auxiliary lines have an ampliative function, adding information to the initially given problem to connect unknowns to knowns. This is a source for unpredictability (Codinhoto 2013): analysis is heuristic, leading to iterations when necessary conditions for proving or constructing a theorem or figure cannot be generated, or the problem is impossible to solve. However, if the necessary conditions are satisfied, synthesis begins with something known and admitted, such as elements of a geometrical figure. As such, synthesis is pre-determined. In rhetoric, the problem and solution are related co-productively and both involve the persuasion of an audience.

Regarding the heuristic nature of the analysis, Umeda et al. (1995) have suggested that decomposition is not a linear single top-down process, but design proceeds in a top-down and bottom-up approach simultaneously. Iterations are inevitable in the design process and can have either positive effects (e.g., knowledge generation, concurrency, or the integrating of changes) or negative effects (e.g., an increase in duration and cost) (Wynn and Eckert 2017). Thus, the management of iterative processes is an important matter in design practice.

Wynn and Eckert (2017) distinguished based on the literature review four common views on iteration: intentional or unintentional iterations (positive or negative); different scales of iteration (macro and micro); the types of change in the design or the tasks being performed; and varying types of iterations not related to previous views. Wynn and Eckert (2017) further proposed the classification of iterative stereotypes according to function: progressive iterations (generation of information and knowledge, driven by uncertainty and problem complexity), corrective iterations (response to unintended results associated with system integration, testing, and design changes), and coordinative iterations (associated with structures and approaches intended to make a process more effective, efficient, and/or predictable). Progressive stereotypes of iteration include exploration, concretization, convergence, refinement, and incremental changes; corrective stereotypes include new work, rework, and churn; and coordinative stereotypes include governance, negotiation, parallelization and comparison (Wynn and Eckert 2017).

However, analysis in design can be logical (Codinhoto, 2013). For example, in the context of structural engineering, if a function (to support loads of a building) is known and the mapping from function to structure (elements and components) is well described, it is hardly discovery but rather the study of the implications of specific solutions.

Design analysis is path-dependent; it is recursive (Ullman 2009). For example, the two-step abductive reasoning proposed by Kroll and Koskela (2016) implies path dependency. Every decision made during the two-step abductive reasoning or in the preceding process stage frames and constrains subsequent decisions, including downstream design decisions and synthesis (making). For example, decisions made in conceptual design bind and constrain the solution space in design development and detailed design phases. The recursive nature of design, i.e., its path dependency, is embedded and illustrated by the 'zigzagging' process in Suh's axiomatic design theory (2001).

In design rhetoric, according to Halstrøm and Galle (2015), "design problems and solutions stand in a chicken-and-egg relation of mutual dependency and therefore in practice tend to evolve in parallel". In other words, problem, solution, and audience spaces co-develop.

8. CREATIVITY

Method of Analysis and Rhetoric: In the method of analysis, creativity is in the introduction of new information in the form of auxiliary lines. Thus, creativity is concerned with drawing inferences backward towards something known and doable. In design rhetoric, creativity is related to three instances, invention (and discovery) of topics (places of inspiration), the arrangement of topics into a whole (creative composition) (Koskela and Ballard 2013), and the expression of ideas.

There are several interpretations of what creativity is in the design context. In technical design, design creativity has been associated with reasoning backward, introducing means (solution principles, structures, properties, and value ranges for properties) to given ends (function and performance requirements). On this basis, Gero (1990) divided design projects into routine projects (with no new variables or ranges in values), innovative projects (where variable value ranges are outside the standard space), and creative projects (where new variables are introduced).

In the argumentative view, in addition to what is useful, the types of innovation are also concerned with what is usable and desirable (Buchanan 1985). From the perspective of what is useful, TRIZ ("theory of the resolution of invention-related tasks") is an example of the use of topoi-like approaches (Tian et al. 2010, Cavallucci 2002). From the perspective of what is usable and desirable, the three-step framework for value celebration, amplification, and judgment proposed by Halstrøm (2017) is a notable example. As for the latter two, Goldhagen (2017) has argued that the effects of the built environment play an active role in human well-being.

In addition, according to Taura and Nagai (2017), there are two modes of creativity, out-of-the-box creativity, which generates ideas that depart from what is believed to be common sense, and compositional creativity, which generates ideas that result from the combination of several elements of knowledge or technology. The former is concerned with the overcoming of fixations, a fundamental tenet of the C-K (Concept-Knowledge) theory, while the other is concerned with the linking of seemingly unrelated ideas, such as the generation of combinations in morphological analysis (Zeiler and Savanovic 2009).

9. WHOLE AND PARTS

Method of Analysis and Rhetoric: In the method of analysis, an analytic inquiry is supposed to start with what is first for humans and end with what is first in nature, while synthesis progresses in the opposite direction. In this process, it is assumed that the relationship between the wholes and parts in the geometric figure are observable (Koskela and Ballard 2013): "a whole can be decomposed into parts and again composed back". In rhetoric, according to Buchanan (2001), invention is concerned with the discovery of topics, wholes (e.g., values, motives, and needs) that are first for humans, the arrangement through creative composition of topics into wholes, and the implementation of individual topics in the medium. The focus of the method of analysis is on the parts, while the focus of rhetoric is on the wholes.

In technical design, it is assumed that the relationships between the wholes and parts are unproblematic and that the value of the solution depends on the quality of partial solutions. The process of 'zigzagging' in axiomatic design theory demonstrates the first assumption (Suh 2001), according to which design is a progression from wholes, overall function, and physical solution to the last, components, from which the thing conceived can be made. In this process, designers are supposed to follow two axioms, the independence axiom (maintain the independence of functional requirements) and the information axiom (minimize the information content of designs).

The quality of partial solutions is exemplified by the V-model by Forsberg et al. (2005). Every step in the left leg of the V-model is supposed to define the partial solutions together with the methods for solution verification and validation in the right leg. In the right leg of the V-model, there is a progression from individual components to assemblies and systems, and at each step, solutions are verified and finally, validated against customer needs.

In design rhetoric, it is assumed that during the design process, in different stages, partial solutions must be integrated into a whole to evaluate the functionality or aesthetics of solutions (Koskela and Ballard 2013). It is assumed that a whole depends largely on arrangement, besides the quality of partial solutions. In software engineering, user stories are used to capture and discover topics of interest (this is the starting point for the functional software system specification), and 'clickable' prototypes, mock-ups, are used to validate customer/user experiences and satisfaction (Sutherland 2014). Thus, the focus is on the effects that the new artefact is supposed to produce. Arrangement has also been a central consideration in architecture, from Vitruvius onwards (Frith 2004).

10. REPRESENTATIONS AND MODELS

Method of Analysis and Rhetoric: In the method of analysis, figures are central to the solving of geometric problems (Hintikka and Remes 1974). In rhetoric, the development of partial designs of speech and testing on oneself or others shows similar features (Kennedy 2007).

According to Eckert and Stacey (2010), it is generally "established wisdom in the design community that models are a useful means of understanding and interacting with both products and processes". Models are vital to design. Models can be about extending a designer's mental operations, for example, in the form of sketches or virtual prototypes, or they can represent an understanding of an artefact or process structure with its constituent parts and relationships or some combination of these (Lindemann 2014). Tversky (2011) described the projection of thought into the world and argued that "when thought overwhelms the mind, the mind puts it into the world, notably in diagrams and gestures" (Tversky 2015). In so doing, humans organize space to convey abstractions (Tversky, 2011).

Models are abstractions of the part of reality they are intended to capture (Maier et al. 2017). Hestenes (2006) defined (a conceptual) model as a representation of structure in a material system, which may be real or imaginary. When a model is described, it has many different meanings, depending on its context of use, purpose, function, behavior, and structure.

Product or process-oriented models are often addressed separately but can also be integrated (Eckert et al. 2017). Models have a certain level of granularity, degree of detail, and specific objective (Maier et al. 2014). High-level models are often generic and have few iterative loops, rendering them of limited value to practicing designers. This limitation has been aptly described by Lawson (1980):

> Knowing that design consists of analysis, synthesis and evaluation will no more enable you to design than knowing the movements of breaststroke will prevent you from sinking in a swimming pool.

Models in the design literature are either descriptive, prescriptive, or both (Wynn 2007). Descriptive models are intended to capture the 'as-is' (causal relationships or the relationships between independent and dependent variables) to increase understanding of phenomena, while prescriptive models attempt to project how things ought to be. Often descriptive and prescriptive models are considered complementary, where the former is used to develop the latter for practice (Evbuomwan et al. 1996, Stumpf 2001).

The typical approach to the development of process models is to begin with a description or prescription of a sequence of stages, e.g., for clarification of the design task, generation of specifications, conceptual design, embodiment design, and detailed design. These process models have been presented in software engineering as a "waterfall" (linear sequential model) (Demir and Theis 2016) and in systems engineering as the stage-gate model (Chestnut 1967).

In technical design, according to Andreasen et al. (2015), functional modelling is concerned with the causal chain, represented by the following sequence: user need > use activity result > determination of use activity > determination of the product's effects and functions > determination of organs and organ structure > determination of parts and part structure. Hardly a practical scheme, this is similar to what Vermaas (2013) proposed when comparing different design ontologies with the definition of function as an essential concept in design. Vermaas (2013) argued that design reasoning about artefacts proceeds from goal, action, function, and behavior to structure. Goal indicates the needs of the user; action is a technical activity determining how users can realize their goal; these actions form a use plan for the device; functions are required to support the action; behavior is the required capacity corresponding to the functions required; and structure is a set of means to achieve expected behaviors (Vermaas 2013).

11. INDIVIDUAL AND COLLECTIVE

Method of Analysis and Rhetoric: When it comes to conceptualizing inquiry from the perspective of an individual or collective, the method of analysis and rhetoric have different scopes. The method of analysis was primarily concerned with an individual's geometrical problem-solving. In the case of rhetoric, design can be conceptualized in two different ways, from the perspective of an individual or as a collective activity embedded in discourse.

In technical design, design activity is generally conceptualized from the perspective of an individual (Stumpf 2001). Similarly, according to Buchanan (2001), rhetoric in design is also rhetoric as practiced by an individual designer.

However, the division of labor has introduced the need for collaboration in design and making. In design practice, designs are co-created by professionals in different specialized disciplines working together to develop an effective means to meet the ends. It is the intention embedded in the design object that links designer to the owner and users, but also designer to designers and makers (contractors) (Halstrøm 2017). The object of communication facilitates the engagement of the designer(s) and customers in dialogue. This agrees with the description of the design activity as a social activity, where scientific knowledge is considered just a starting point for design inquiry.

An example of the interplay between the individual designer, a collective, and their design objects was given by Bucciarelli (1994) in his ethnographic study of engineering design:

> The thesis of this book is that the process of designing is a process of achieving consensus among participants with different "interests" in the design, and that those different interests are not reconcilable in object-world terms. The process is necessarily social [...] This is not to deny the importance of scientific and technical constraints and specifications [...] science matters in that it provides the underlying form of design [...] in more general sense, is the mode of thinking within object worlds [...] structures the way in which participants frame their work process and interactions [...] I argued that, while science and markets have roles to play in design, they are far from decisive.

Thus, the view of design as an individual working within his or her domain, driven by underlying scientific modes of thinking, and the view of it as a collective effort are both essential to the conceptualization of design activity.

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Appendix III: Research Materials and Methods in Case Study I

SIMULATION MODELS FOR EXPERIMENTATION

Each apartment, corridor, and stairway was modelled as a separate zone, and the Estonian methodology for calculating the energy performance of buildings (MKM 2012) was used. Well-validated simulation software IDA ICE 4.6 (IDA-ICE 2014) and an Estonian test reference year were used when performing energy simulations (Kalamees and Kurnitski 2006, Yang et al. 2011). Estonian regulations require that the indoor temperature in residential buildings not exceed a limit temperature of 27 °C by more than by 150 °Ch (degree hours). Originally, district heating with radiators (ideal heaters in the model) and mechanical supply and exhaust ventilation with heat recovery were used. The usage factor for heat gains was generally 60%, and ventilation was in operation at all times. The primary energy factor for district heating is 0.9, which is equivalent to approximately 280 kg CO_2/kWh, and for electricity, it is 2.0, which is equivalent to approximately 920 (kg CO_2/kWh), according to Estonian energy statistics. The initial data for the simulation model is shown in **Table 1**. In this study, we did not consider global climate warming in the cold climate of Estonia, where heating is more dominant than cooling. However, according to Li et al. (2012) and Yang et al. (2014), it could have a significant impact on energy consumption and needs to be addressed in future studies.

Table 1. Input data parameters for apartments and HVAC systems for energy calculations. Abbreviations: SFP – specific fan power, ηT – heat recovery temperature efficiency, DHW – domestic hot water.

Occupants, W/m^2	3
Occupant density, m^2/person	28
Average Use Level, %	60
Equipment, W/m^2	3[a]
Lighting, W/m^2	8[b]
Setpoint temperatures for heating, °C	21
Heating supply water temperature, °C	90
Heating exhaust water temperature, °C	70
Air flow rate, l/(s·m^2)	0.42
Supply air temperature, °C	18.0
Minimum exhaust air temperature for cross-flow plate heat recovery, °C	5.0
Minimum exhaust air temperature for rotary heat recovery, °C	0
SFP, kW/(m^3/s)	1.5
Ventilation η_T, % (cross-flow/rotary heat exchangers)	88/80
Annual DHW consumption, l/m^2	520
Hot Water Temperature, °C	70-90
Boiler Efficiency/COP	1
Peak Distribution Efficiency, %	0.85

[a] – the heat gains for equipment were divided by 0.7 to calculate delivered energy
[b] – the usage factor for lighting was 0.1

VENTILATION UNITS

Originally, a ventilation unit with cross-flow heat recovery was installed in each apartment. In this study, cross-flow and rotary heat exchangers are compared. The units had a high temperature recovery efficiency of 88% and 80%, respectively, with a specific fan power (SFP) of 1.5 kW/(m3/s), and can thus be considered as energy efficient. The ventilation systems were simulated with exhaust air temperature limited to +5 °C in the case of cross-flow heat exchangers and 0 °C in the case of rotary heat exchangers (MKM 2012). The prices for the ventilation units were obtained from a local distributor and validated by a local general contractor. The cost of an air handling unit with cross-flow plate heat recovery was 1300 € + VAT (value added tax). The cost of an air handling unit with rotary heat recovery was 1200 € + VAT.

SOLAR THERMAL COLLECTORS

Originally, no renewable energy production technology was installed in this case building, but by definition, nZEB assumes local energy production. Therefore, we analyzed the financial feasibility and energy potential of solar thermal collectors and photovoltaic (PV) panels. The area of the solar collectors was calculated using a simplified method described by Walker (2013):

$$A_c = \frac{Q_{load}}{I_{c,\max} \times \eta_{solar}} \quad (3)$$

where A_c is collector area (m²); Q_{load} is daily hot water energy load, 243 kWh/d for the given building, $I_{c,max}$ is the maximum daily solar radiation expected over the course of the year, 5.1 kWh/m²/day; and η_{solar} is the efficiency of the solar energy system averaged over the day, 30%.

The maximum solar collector area that could be installed was estimated to be 225 m², but in this study, solar collector sizes over 200 m² were not analyzed. Solar collector information was obtained from a local reseller, and for analysis we considered a unit with an area of 2.51 m² (1.05 m wide and 2.38 m long), an energy conversion factor of η_0=0,793, a_1 (first order heat loss coefficient) equal to 3.95 W/(m² K), and a_2 (second order heat loss coefficient) equal to 0.0122 W/(m² K). The areas analyzed and their corresponding domestic hot water accumulation tank volumes and system prices are given in **Table 2**. The tank volumes did not exceed 4000 liters, as these were comparable to daily hot water consumption volume. The prices for solar collectors and installations (i.e., collectors, piping, heat substation, accumulator tank, accessories, and installation) were obtained from a local contractor.

Table 2. Solar collector areas considered, corresponding accumulation tank volumes, and installation costs of the system.

Collector area, m²	Accumulation tank size, liters	Cost per installed collector area, €/m²
25	1000	772
50	1750	618
75	2500	603
100	3000	564
125	3500	552
160	4000	521

CALCULATION OF PV NOMINAL POWER AND PRODUCTION

As in the case of solar collectors, the maximum PV area that could be installed was estimated to be 225 m^2, but in this study, PV sizes exceeding 200 m^2 were not considered. To calculate the energy production efficiency of a 1 kW PV panel, the Estonian Ordinance no. 58 "energy-efficiency calculation methodology" was followed (MKM 2015). According to this methodology, annual PV electricity production is calculated using the following equation (1).

$$E_{Panel} = \frac{Q_{Solar}\, P_{Max}\, k_{Use}}{I_{Ref}} \qquad (1)$$

where E_{panel} is the annual energy production (kWh/a) for the PV panel; Q_{solar} is annual solar radiation (kWh/m^2 a); P_{max} is maximum power for the PV panel under standard conditions (kW) (I_{ref} = 1 kW/m^2, temperature = 25 ^{o}C); k_{use} is a factor that takes into account unique site conditions (temperature, panel installation) and losses (0.7 for non-ventilated PV panels, 0.75 for moderately ventilated panels, and 0.8 for intensively ventilated panels); and I_{ref} represents standard radiation (1 kW/m^2). To calculate E_{panel}, we first need to calculate Q_{solar}, which is the annual solar radiation falling on a PV panel. It is calculated according to the following equation (2).

$$Q_{solar} = 960 * k_{orien.} * k_{angle} \qquad (2)$$

where 960 represents annual solar radiation on a horizontal surface; $k_{orien.}$ is a factor that takes into account the orientation of the PV panels (1 for South-East/South/South-West, 0.8 for East/West, and 0.6 for North-West/North/North-East); and k_{angle} is a factor that takes into account the angle of the PV panels relative to the horizon (1 when the angle is <30^o, 1.2 when the angle is from 30–70^o, and 1 when the angle is >70^o).

When calculating Q_{solar}, it is assumed that the panels are directed either towards the South-East/South/South-West ($k_{orien.}$=1) and that the angle of the panels is between 30–70^o (k_{angle}=1.2). However, a shading factor was used to evaluate the robustness of the PV systems for two reasons: first, there are no studies that have investigated the conditions for a typical PV system installation, and secondly, PV systems are not built where conditions are ideal, while, for example, there might be shading trees or neighboring buildings. Based on these assumptions, PV system capacity and annual production were calculated, with the result that electrical energy delivery to the site would be reduced. In turn, the assumption was made that excess energy would be sold back to the grid, leading to reduced primary energy and net present value.

FINANCIAL CALCULATIONS

When calculating the impact of robustness on cost optimality, a 30-year net present value (NPV) is used in the comparison of the financial feasibility of different cases. The NPV includes investment cost and the energy costs discounted to present day value. The calculation of energy savings and NPV, according to the Commission's cost optimality methodology (Council 2012), relied on the following parameters:

- NPV calculation and loan period: 30 years;
- Real interest rate: 3%;
- Heating energy (district heating) cost: 0.075 €/kWh (VAT included);

- Escalation of heating energy costs: 1% (adjusted for inflation);
- Cost of electricity: 0.0943 €/kWh (including VAT);
- Rate for selling electricity: 0.0150 €/kWh;
- Escalation of electricity costs: 1% (adjusted for inflation);
- The present value factor for heat (equation 6): $f_{pv}(n) = 22.4$.

Energy costs were calculated per building heated area, and NPV was calculated as follows:

$$C_g = \frac{C_I + C_a \times f_{pv}(n)}{A_{floor}} \qquad (4)$$

where C_g is global incremental energy performance related costs included in the calculations, (€/m²); C_I is energy performance related construction costs included in the calculations (€); C_a is annual energy costs during the starting year (€); $f_{pv}(n)$ is the present value factor for a calculation period of 30 years; A_{floor} is net heated floor area (m²).

To calculate the present value factor $f_{pv}(n)$, the real interest rate R_R was calculated; this is dependent on the market interest rate R and inflation rate R_i:

$$R_R = \frac{R - R_i}{1 + R_i/100} \qquad (5)$$

An inflation rate of 1% (R_i) was used in the calculation of the real interest rate. To calculate the percent value factor, the escalation rate e must be subtracted from the real interest rate R_R (Council, 2012).

The present value factor $f_{pv}(n)$ for a calculation period of 30 years is calculated as following (Pikas et al., 2014c):

$$f_{pv}(n) = \frac{1-(1+(R_R-e)/100)^{-n}}{(R_R-e)/100} \qquad (6)$$

where R_R is the real interest rate (%); e is escalation of energy prices (%); and n is the number of years being considered, i.e., the length of the calculation period.

ROBUST DESIGN METHOD AND PRINCIPLES

The point of applying robust engineering principles was to find a combination of control factors (design parameters that designers can select) that meet the cost optimality requirement and was the least sensitive to varying environmental conditions (Taguchi et al. 2005). Internal noise factors were not considered, as this study is concerned with the conceptual design stage, where designers are dealing with idealized concepts (Taguchi et al. 2005).

According to robust design, also called the Taguchi method, the design phase is divided into system design, parameter design, and tolerance design (Taguchi et al. 2005). In this case study, the focus is on system design using parameter design principles. Robust parameter design consists of the following steps (Wu and Wu 2000):

1. Define the ideal function – In this study, a 30-year NPV was chosen as the ideal function to estimate life-cycle costs with respect to initial investment.
2. Select control factors and their levels – These were described in the case study.

3. Select reasonable noise factors, forecast their ranges, and compound them – Identify noise factors that are expected to have the highest impact on designs. The chosen noise factors should then be compounded, meaning that extreme conditions are set for the factors.
4. Select S/N (signal-to-noise) ratio – the S/N ratio was selected based on the ideal function.
5. Prepare the orthogonal arrays - Control factors are placed in the inner array and noise factors in the outer array.
6. Conduct the designed experiment.
7. Calculate the S/N ratios.
8. Do a 2-step optimization:
    a. From the response table, select control factor levels with a higher S/N ratio to reduce variability around the average.
    b. From the response table, select control factors whose level changes do not have a strong effect on the S/N ratio but do affect the average, to adjust the mean to the target.
9. Forecast the optimum condition – The forecast is based on the cost optimization.
10. Run a confirmatory experiment – The optimum condition is used to conduct a confirmatory experiment to ensure the conclusion is reproducible.

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Appendix IV: Survey Questions in Case Study III

Interview questions

These questions were prepared to evaluate the opinions of employees about the current situation in the company regarding the quality of designing and design management. Both designers and project managers were asked to rate statements related to design management and organizational issues on a five-point Likert scale from strongly disagree to strongly agree.

General Questions

1. Please indicate the department you are working in:
   - Architecture
   - Structural Engineering
   - Building Services
   - Project Management
2. Please indicate how many years of work experience you have:
   - <2 years
   - 3-5 years,
   - 6-9 years,
   - 10-14 years,
   - >15 years)
3. Please rate the following statements related to design management and organizational issues on a five-point Likert scale from strongly disagree to strongly agree:
   - Either team members or the customer make last minute changes.
   - If I had more time I would do my work and projects differently.
   - I believe I know why and where projects go wrong.
   - Cross-disciplinary coordination is poor.
   - It is often uncertain when I will get necessary input from other designers.
   - Clients do not solve problems in a timely manner.
   - I have limited time to do my project work.
   - I could do my projects better if my knowledge were more sufficient.
   - We often postpone dealing with problems that should have been dealt with immediately.
   - Other team members have poor qualifications and experience.
   - Other team members are not available when needed.

Appendix V: Detailed Process Models for Project Planning and Other Phases in Case Study III

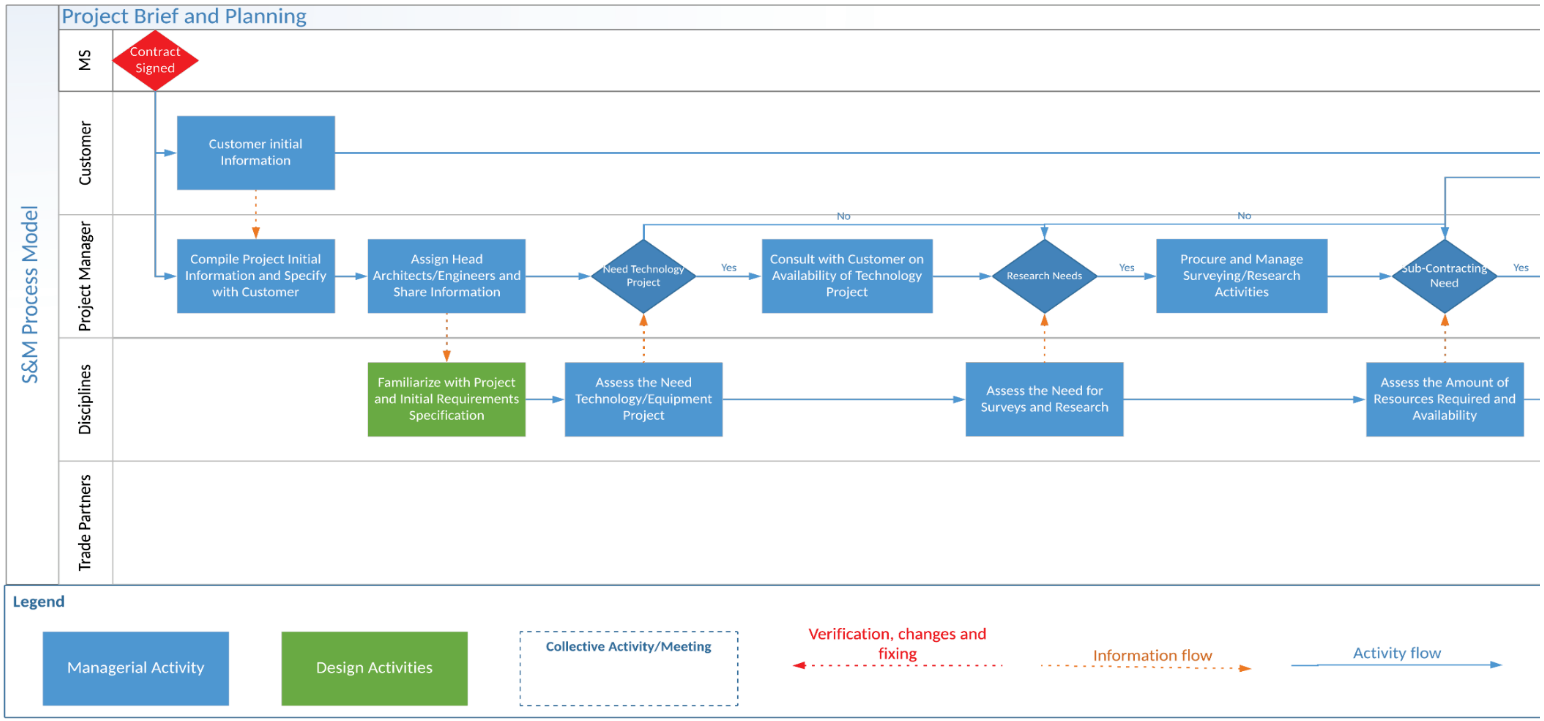

Figure 1a. Process description for project planning.

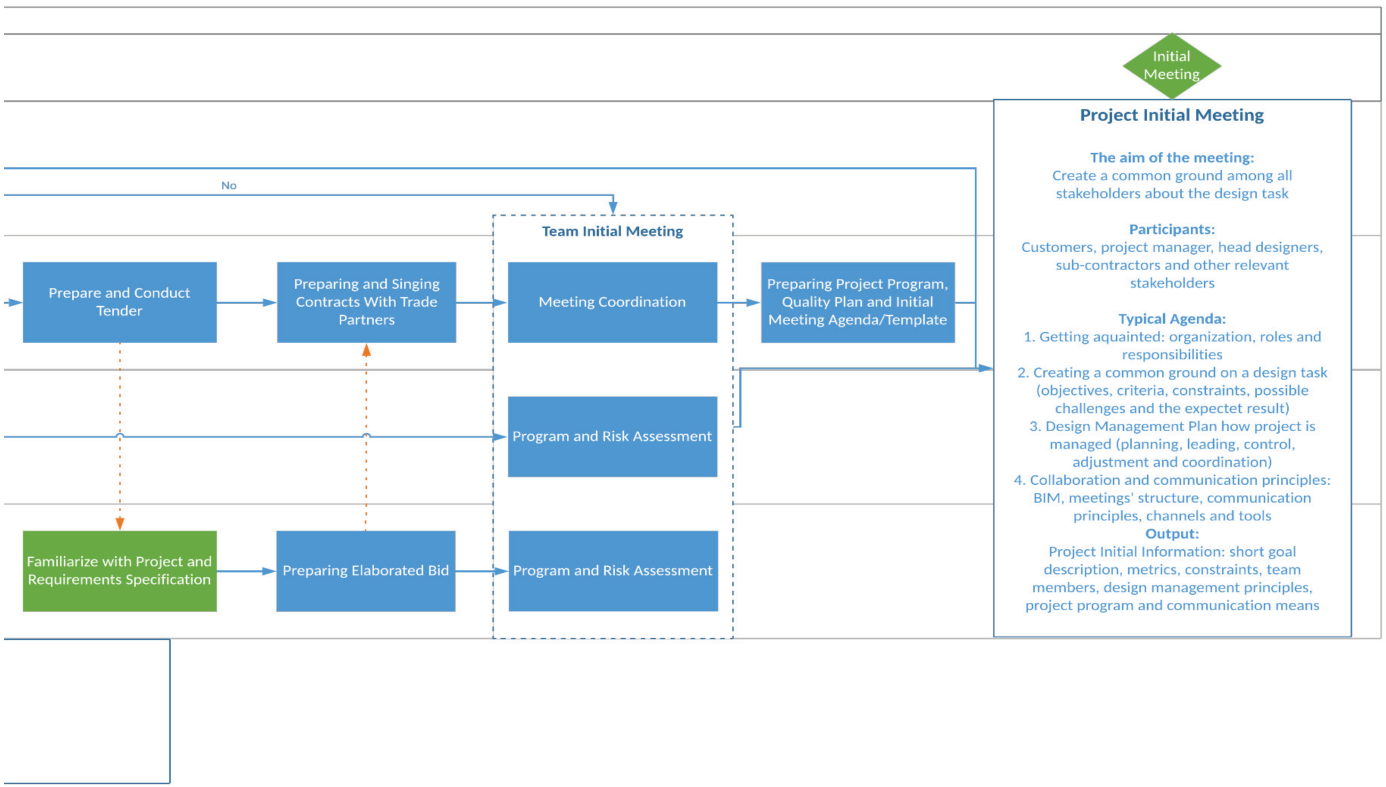

Figure 1a. Process description for project planning.

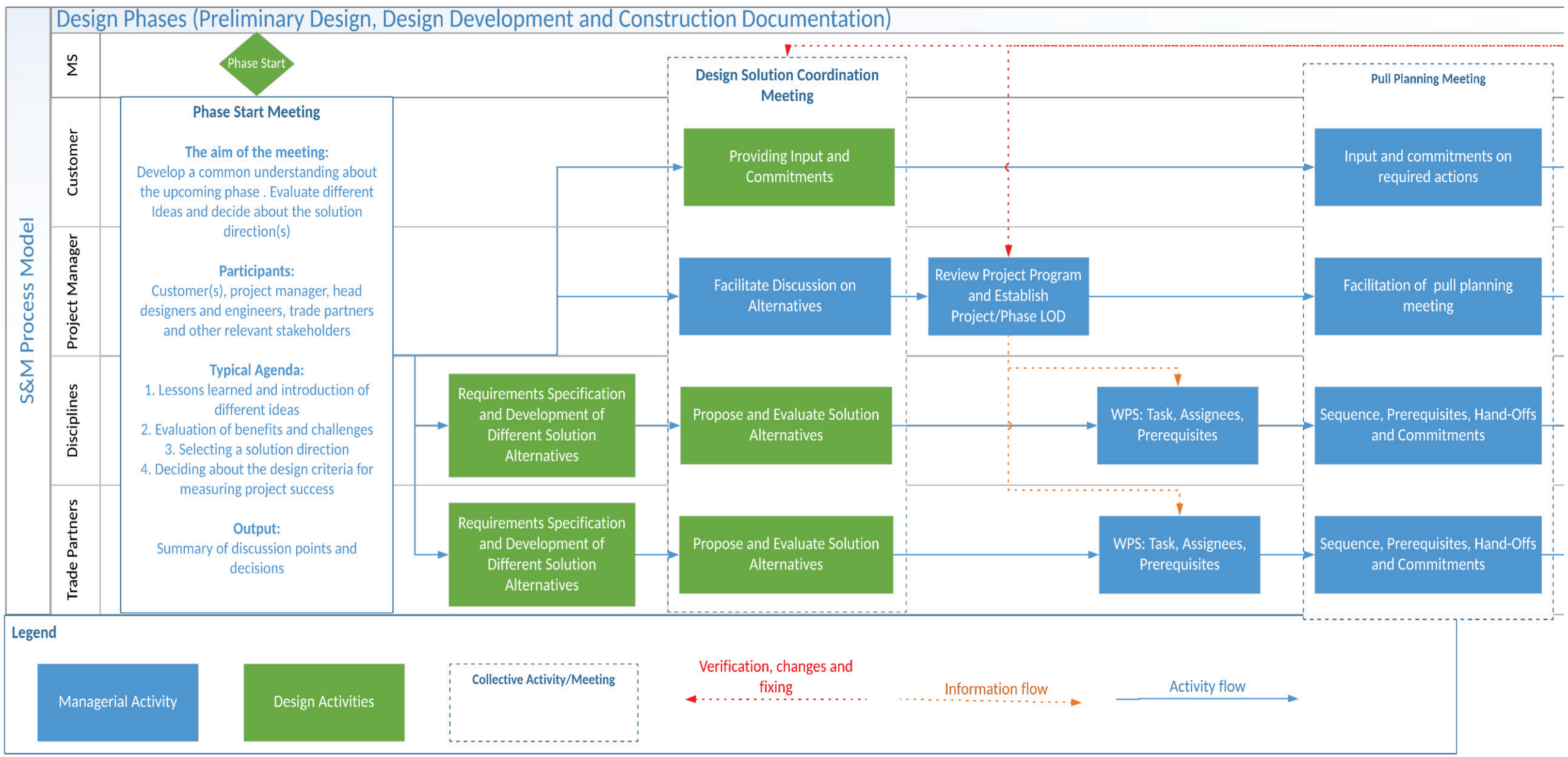

Figure 2a. Process description for project phases.

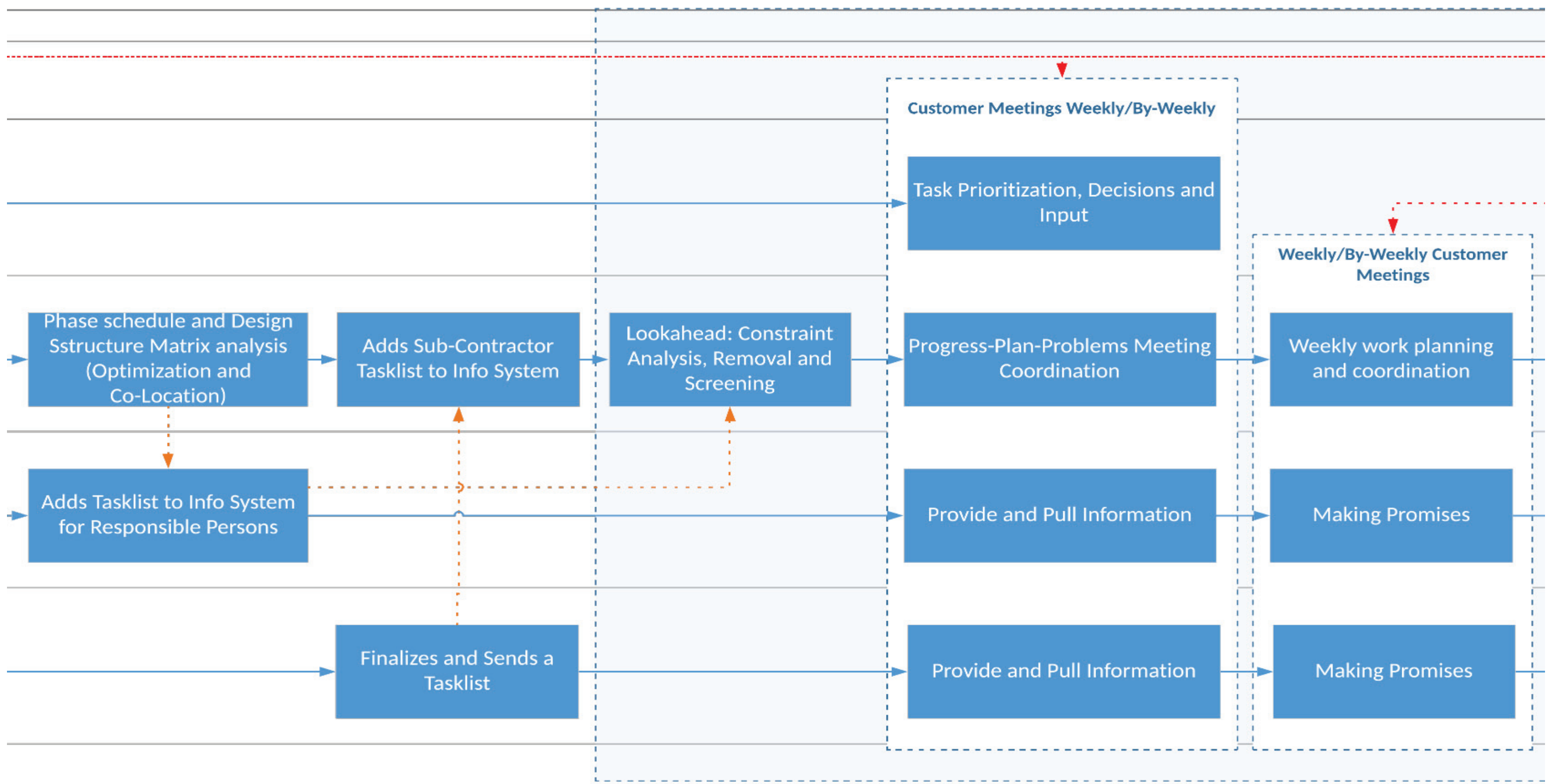

Figure 2b. Process description for project phases (continued).

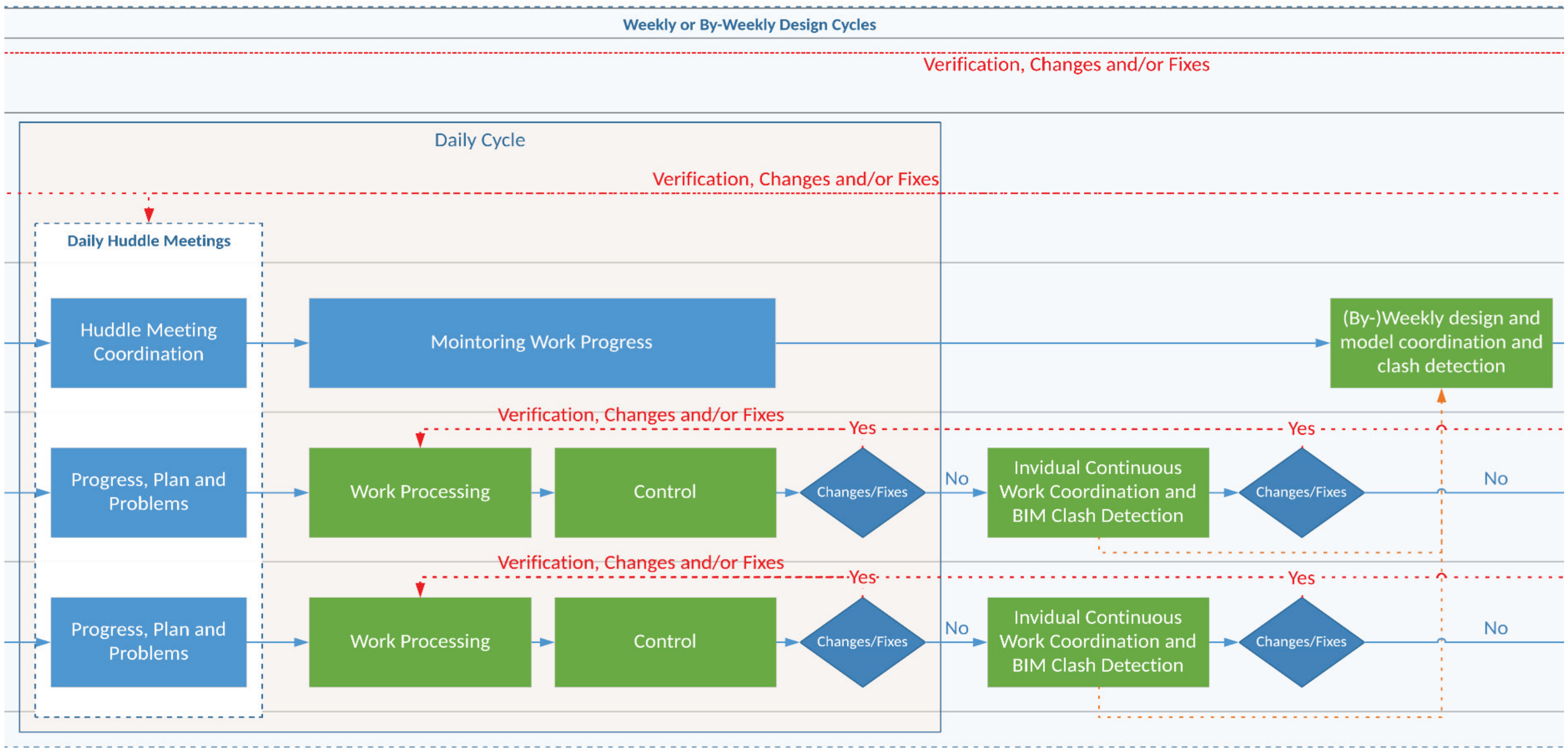

Figure 2c. Process description for project phases (continued).

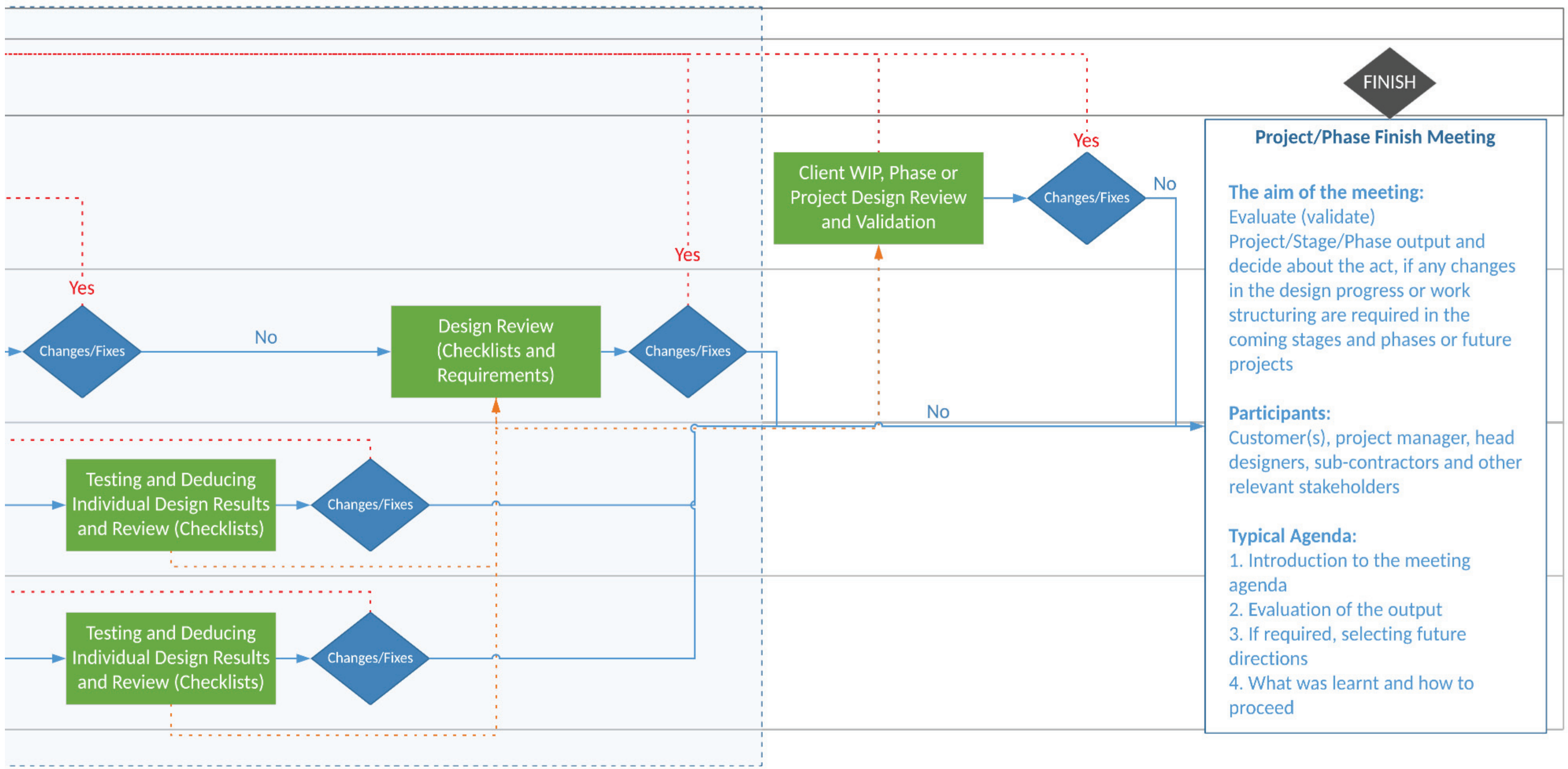

Figure 2d. Process description for project phases (continued).

Curriculum Vitae

PERSONAL DATA

Name	Ergo Pikas
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EDUCATION

2014–...	**Aalto University, Department of Civil Engineering, Finland**
SUBJECT	Pursuing the degree of Doctor of Science, Technology
DISSERTATION	Causality and Interpretation: Integrating the Technical and Social Aspects of Design
SUPERVISOR	Prof. Dr. Jari Puttonen, Aalto University, Department of Civil Engineering, Finland
ADVISOR	Prof. Dr. Lauri Koskela, University of Huddersfield, School of Art, Design and Architecture, UK

2014–...	**Tallinn University of Technology, Department of Civil Engineering and Architecture, Estonia**
SUBJECT	Pursuing the degree of Doctor of Philosophy, Engineering
DISSERTATION	Causality and Interpretation: Integrating the Technical and Social Aspects of Design
SUPERVISOR	Prof. Dr. Roode Liias, Tallinn University of Technology, Department of Civil Engineering and Architecture, Estonia
ADVISOR	Prof. Dr. Jarek Kurnitski, Tallinn University of Technology, Department of Civil Engineering and Architecture, Estonia
ADVISOR	Prof. Dr. Lauri Koskela, University of Huddersfield, School of Art, Design and Architecture, UK

2016-2017	**University of California, Berkeley, USA**
SUBJECT	Fulbright Visiting Student Researcher

2010-2012	**Technion – Israel Institute of Technology, Department of Civil and Environmental Engineering, Israel**
SUBJECT	Master of Science
DISSERTATION	Evaluation of University-level BIM Education in Construction Engineering and Management
SUPERVISOR	Prof. Dr. Rafael Sacks, Technion – Israel Institute of Technology, Department of Civil and Environmental Engineering, Israel

2006-2010	**TTK University of Applied Sciences, Institute of Civil Engineering, Estonia**
SUBJECT	Bachelors of Applied Sciences
DISSERTATION	Integration of Lean construction (LC) and Building Information Modeling (BIM)
SUPERVISOR	Prof. Dr. Roode Liias, Tallinn University of Technology, Department of Civil Engineering and Architecture, Estonia Prof. Dr. Rafael Sacks, Technion – Israel Institute of Technology, Department of Civil and Environmental Engineering, Israel

2003-2006	**Kiviõli I Secondary School, Estonia**
SUBJECT	High school education, Graduated with the letter of commendation

TEACHING EXPERIENCE

Lecturer (2014-to 2016): Building Information Modelling II (BIM II), Integrated degree, Faculty of Civil and Env. Engineering, Tallinn University of Technology.

Lecturer (2014-to 2016): Building Information Modelling I (BIM I), Integrated degree, Faculty of Civil and Env. Engineering, Tallinn University of Technology.

Teaching Assistant (2011-2012): Engineering Information, Undergraduate, Faculty of Civil and Env. Engineering, Technion.

Teaching Assistant (2011-2012): Introduction to Construction Management, Undergraduate, Faculty of Civil and Env. Engineering, Technion.

Teaching Assistant (2011-2012): Advanced Building Information Modelling, Graduate, Faculty of Civil and Env. Engineering, Technion.

LANGUAGE COMPETENCE

ESTONIAN	Mother tongue
ENGLISH	Fluent
RUSSIAN	Basic
HEBREW	Basic

PROFESSIONAL EMPLOYMENT

2017–	Technical University of Denmark, Copenhagen, Denmark: Researcher
2016–	LODplanner Ltd, Orange County, USA: Advisory Board
2015–2018	Leansite OÜ, Tallinn, Estonia: Co-Founder and Product Manager
2012–	Gravicon EE OÜ, Tallinn, Estonia: Co-Founder and Development Manager
2012–2016	Tallinn University of Technology, Tallinn, Estonia: Early Stage Researcher
2012–2014	Ministry of Economic Affairs and Communications, Tallinn, Estonia: Executive Officer/Project Manager
2010–2010	Salford Centre for Research and Innovation, Manchester, UK: Research Assistant
2009–2009	Telora-E Ltd, Tallinn, Estonia: Project manager assistant