Entrepreneurship with Additive Manufacturing: Implications of Complexity Freedom in Product and Firm Ideation

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Dedication

Para Karen, Mamá, Papá, Abuelito Ricardo y Abuelito Albino.

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Abstract

The diffusion of 3D printing technologies after the expiration of key patents in 2009 brought novel manufacturing applications beyond prototyping (Thompson et al., 2016). Particularly, *Additive Manufacturing* (AM) has enabled more integrated strategies for new product development and fabrication. As a result, AM has been considered as a promising instrument for new business creation (Rayna & Striukova, 2016). Studies concerning AM and entrepreneurial activity rarely consider the interactions with technology. Yet, theories that describe the relationship between product architecture and manufacturing organizations suggest that greater flexibility in product architecture would bring greater flexibility to the creation of the firm through a process of *mirroring* (Colfer & Baldwin, 2016). Additionally, the theory of effectual entrepreneurship describes the creation of markets as negotiations between entrepreneurs and possible partners with the product and the means of the entrepreneur at the centre of such negotiations (Sarasvathy & Dew, 2005; Zahra et al., 2006). The research presented in this thesis examines the idea that flexible product architecture in 3D printing gives entrepreneurs greater flexibility in product design and an increased flexibility in the acquisition of partners.

Two studies were carried out under a grounded methodology to explore the effects of complexity in the ideation of business opportunities. Both studies are based on design exercises that study the impact of idea generation using imaginary images, sketches, and prototypes in design (Finke, 1996; Kudrowitz & Wallace, 2013). The first study included seven teams of participants who used a building set with the same budget conditions and objectives. The control group received traditional production costing, while the AM one received free complexity costing. Idea complexity was measured in the number of blocks used to build each component, and the number of connections in each joint. The second study consists of an ideation exercise where 308 participants interpreted abstract randomized images of objects of varying complexity to imagine possible future product and firm participants. Their responses were analysed to extract networks of product categories and stakeholder identities. Answers were evaluated in terms of novelty, literality, and network composition.

The results of both studies challenge some of the arguments that explain the benefits of additive manufacturing as increased freedom in product design. Instead, the results suggest that *complexity freedom* is filtered through the manipulation of morphology in design exploration. This argument advocates for an embodied design exploration where the perceptual features of technology influence ideation.

This thesis contributes to the understanding of the relationships between additive manufacturing, entrepreneurship, and design. The studies presented here highlight the need to reconsider claims made in recent years about the advantages of increased flexibility for entrepreneurship with the introduction of additive manufacturing. In addition, the focus on technological interfaces expands the domain of entrepreneurship and firm design including perception, which is not accounted for in strategy and business modelling.

Co-authored Publications

The following publications were written based on the results of the studies presented in this thesis. While both publications are majorly produced by the author of this thesis, the quality of the contributions is listed as follows:

Esparza, A., Sosa, R. & Connor, A. (2017) The Shape of Firms: Opportunities from Rapid Manufacturing. In A. Reyes-Munoz, P. Zheng, D. Crawford, V. Callaghan. (Eds.) *EAI International Conference on Technology, Innovation, Entrepreneurship and Education TIE'2017.* Lecture Notes in Electrical Engineering, vol 532. Springer. 249-262. https://doi.org/10.1007/978-3-030-02242-6_19

	Percentage	Contribution	Signature
Jose Antonio Esparza Flores	80%	Theory and Design, Writing.	
Ricardo Sosa	15%	Theory and Design, Writing.	
Andrew Connor	5%	Writing.	

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	Percentage	Contribution	Signature
Jose Antonio Esparza Flores	80%	Theory and Design, Implementation of Methods, Analysis, Writing.	
Ricardo Sosa	15%	Analysis, Writing.	
Andrew Connor	5%	Analysis, Writing.	

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Attestation of Authorship

“I hereby declare, that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning”

Jose Antonio Esparza Flores

1 Introduction: The Firm Design Process

1.1 Study Rationale

Entrepreneurship is often determined by design and technological factors. However, most studies of entrepreneurship have been conducted within a scope that does not recognize the inner workings of technology, thus providing a limited consideration of such factors. Examples of these studies provide an organizational perspective, where the product and technology used remains in the abstract and focus on the explanation of management concepts (e.g. Nambisan, 2017; Petrick & Simpson, 2013; Svenja C. Sommer et al., 2008). Yet, the development of 3D printing affects strategic, design and technological factors and creates new opportunities for business ventures that are radically different to the existing manufacturing alternatives. Likewise, the development of 3D printing encourages the study of entrepreneurship under such specific circumstances.

3D printing has been under development for thirty years and is currently broadly applied in the fabrication of prototypes in new product development. These technologies gained popularity in the last decade due to the expiration of patents for Fused Deposition Modelling (FDM) technology in 2009. This incentivised the appearance of desktop units and significantly reduced costs (Deutscher et al., 2013). This has further increased the use of 3D printing in manufacturing conditions thus identified as *Additive Manufacturing* (AM). Contrary to other fabrication methods, AM has the potential to reduce the amount and variety of equipment required for the introduction of new products (D. Thomas, 2015). Consequently, entrepreneurs can design and produce artefacts with a high level of complexity with minimum investing. With the diffusion of 3D printing into mainstream markets, researchers forecasted new forms of employment, organizational structures, and business s (I. Gibson et al., 2015; Petrick & Simpson, 2013).

The benefits of AM technologies stem from their capability to deposit material only where the geometry requires it. AM uses digital models to *slice* the geometry in layers as thin as the minimum thickness allowed by the machine and the material (Section 2.1.5). The printer deposits only the necessary material layer by layer usually in powder or liquid form that solidifies to form a physical product. As a result, the production of two geometries of different complexity and the same volume uses the same amount of resources and hence, the same cost. This is a significant change because traditional manufacturing processes rely heavily on the subtraction of material, which adds machining operations every time a new feature is included in the manufactured product. This *complexity freedom* of AM technologies breaks the rules that bound manufacturers to economies of scale since fabrication is not tied to the production of tooling specially designed for one product only. As a result, researchers have proposed that entrepreneurs that use AM have the flexibility to explore business model configurations that exploit the new capabilities to modify and produce highly complex artefacts with minimum investment (Rayna & Striukova, 2016).

Studies that address the implementation of 3D printing come mainly from the fields of Entrepreneurship and Technology Management. Entrepreneurship research that describes processes for the implementation of AM portray it as a technology that can be used for the generation of disruptive strategies. It is proposed that it can be used in different degrees of implementation from prototyping to full manufacturing (Mellor et al., 2014) and have the potential to explore adjacent markets and experiment with the integration of the supply chain (D. Thomas, 2015). However, the capabilities of 3D printing echo in other branches of entrepreneurship research that situate the product at the core of the market opportunity (Sarasvathy & Dew, 2005).

Theories of entrepreneurship creation propose that market opportunities are built through the enactment of the means around the entrepreneur (Alvarez & Barney, 2007). Such theories overlap with, the study of technology management proposes that markets and industries are built around successful product architectures (Murmann & Frenken, 2006). The models of dominant designs posit that product architectures mirror the communication amongst the stakeholders that manufacture the product (Colfer & Baldwin, 2016). Successful product architectures shape industries and extend their influence on competitors. This thesis evaluates the use of AM for the enactment of the entrepreneurial resources and the control of the *mirroring process* as an entrepreneurial strategy.

The present thesis critically examines the interaction of entrepreneurs with AM technology. This work focuses on complexity freedom and the effects it has on the generation of market opportunities. The research views the *entrepreneurial ideation* process as a *design exploration* where the manifestation of business ideas influences the available solution space for the entrepreneur. Two studies were implemented where participants interact with design representations of different complexities with the purpose of creating a market opportunity. This thesis seeks to increase our understanding of how entrepreneurs generate ideas and the interaction with the means they have.

1.2 Aim of Study

The theories of entrepreneurship creation and architecture mirroring address the creation of market institutions (customers, suppliers, regulators, and other stakeholders). For instance, theories of creative entrepreneurship suggest that the context is enacted to ideate and create associations between stakeholders. Particularly the concept of the "effectual contract" suggests that this enactment happens through the negotiation of the features of a product or value proposition between stakeholders (Sarasvathy & Dew, 2005). The accumulation of contracts creates a network of bystanders with roles that eventually constitute the market institutions. On the other hand, the mirroring of product architecture proposes that the relationships between components will be mirrored by the organizational structures that must negotiate for its design (Colfer & Baldwin, 2016). Through time, the crystallization of such negotiations reduces the uncertainty in the production of interfaces and turns components into commodities. This commoditization allows the manufacturing organization to share component information with suppliers and regulators, thus creating market institutions. It is argued here that both sets of theories describe the same phenomenon of market creation with models that correspond to methods and concerns of their respective research domains. Accordingly, entrepreneurs that seek to start a business with AM are not able to appreciate a joint theory of market creation that can be places in a 3D printing context.

Since AM merges design and manufacturing, it is relevant to examine the creation of a business venture and the product architecture within it considering 3D Printing as a starting condition (Petrick & Simpson, 2013). Contrary to other manufacturing processes where NPD can be considered a staged process, the complexity freedom in AM supports the iteration of product architecture in every manufacturing round. Consequently, the configuration that will be negotiated and mirrored in the network of stakeholders can also be transformed with every iteration. Therefore, the gradual creation of markets described in the arguments above has the potential of becoming an iterative process of market creation with AM. 3D printing research has described possible scenarios for the exploration of new product architectures (Conner et al., 2014). However, these scenarios are limited to the speculation of product performance and show no evidence to support the utilization of AM in the creation of markets.

This thesis has the aim of articulating the bodies of creative entrepreneurship and technology management as design processes with the purpose of evaluating the capabilities in AM to design market structures. This articulation of the theses of market creation requires the analysis of both processes of creation and their underlying design principles. Hence, this thesis puts forward a proposition that separates the process of firm design within the creation of markets for analysis. The confirmation of the positive effects of AM in the creation of markets would depict 3D printing as a tool for the leverage of product architecture in market creation. Thus, this research project questions the effects of using AM in the ideation of business opportunities:

Q1. How does complexity freedom impact early entrepreneurial ideation?

Q1a. How does complexity freedom affect product architectures in entrepreneurial ideation?

Q1b. How does complexity freedom affect the structures of ideated business opportunities?

1.3 Contribution

This research project provides evidence to question the assumed cognitive processes of design that happen in ideation processes within the creation of organizations with technology. It suggests that functional allocation in product design that is described as the blueprint for market creation is not directly present in entrepreneurial ideation. It introduces the role of morphology instead of complexity as an important factor in the creation of possible scenarios for market effectuation. In relation to AM, it contributes to show a void in the way research around AM speculates about possible scenarios. It suggests that further research around the influence of morphological traits of the technological means is needed in order to create effective tools for the implementation of AM technologies.

This thesis also contributes to the understanding of firm design as a different domain within and not equal to the study of market creation. It suggests the separation of the firm as an artefact made from contracts and separate from the central issues of the theories that already describe entrepreneurship and technology management. It also proposes a change in the ontological underpinnings of the fields to integrate the methods that study the implementation of 3D printing in new business ventures. The thesis compares the nature of the firm as an artefact with current definitions and popular models.

The motivation for this research project comes from gaps found in the experimentation with 3DPrinting in the creation of new business models. Entrepreneurship is often understood as a venture with opportunistic motivations nevertheless, the most pervasive manifestation of this phenomenon is motivated by the need to adapt to changing economic conditions (Global Entrepreneurship Research Association, 2017). These necessity – driven ventures feature value propositions that look for cost-leadership instead of innovative differentiation based on the restricted nature of their resources (Block et al., 2015). Accordingly, the flexibility of these ventures to experiment in different products is restricted. The presence of 3DPrinting challenges this resource restriction by removing the complexity cost in the design process. Yet, to the knowledge of this research project, there are not documented cases of entrepreneurship that feature a differentiation strategy at a small scale and in a necessity – driven venture.

The author of this research project experimented with the fabrication of moulding matrixes for the retail of ceramic products between 2012 and 2015. During this period advantages were found in the use of 3DPrinting as a method to adapt product design and business model concurrently.

1.4 Structure of the Thesis

The nature of 3DPrinting brings together phenomena that otherwise can be studied separately in conventional manufacturing scenarios. While in conventional scenarios, the development of new products and new business venture is staged and can be "frozen", in the case of 3DPrinting, the stages of such development merge. This has brought scholars to draw knowledge from bodies that are commonly used to explain a "staged" phenomenon into a liminal one. Therefore, this thesis attempts to question the frameworks used to guide the creation of businesses with 3DPrinting by connecting them to the bodies of knowledge where they are drawn from.

The review of concepts in this thesis scopes research from different disciplines at different levels of abstraction, from high- level abstraction theories that explain phenomena such as creative cognition, to prescriptive frameworks proposed to guide the implementation of technology and the creation of business ventures. Accordingly, this thesis faces the challenge of categorizing the working concepts of three different research disciplines without confounding the way they articulate together. The structure of the thesis uses a differentiation proposed by a review of concepts (Galle, 2018; Nilsen, 2015; Sutton & Staw, 1995). Thus, this thesis divides its working concepts in three categories in order to guide the reader*: bodies, theory*, and *frameworks*. The words *research, domain*, and *discipline* correspond to the complete bodies of knowledge (both abstract and concrete) that belong both to a field and a group of researchers. The terms *theory* and *model* refer to *theories of science*, that make a detailed description of a phenomenon with a high level of abstraction. On the contrary, words such as *framework* and *process*, refer to constructs of low level of abstraction that are used to translate research into practice and refer to instantiations of theories such as those that happen in the implementation of 3DPrinting.

This thesis introduces four main theoretical concepts from a reinterpretation of the cognitive processes used during the design of artefacts in the study of entrepreneurship, technology management, and 3DPrinting: the effectuation of market opportunities, the mirroring process of product architecture, complexity freedom in 3D Printing, and design as exploration. Together they are articulated to question the assumptions in the implementation of 3DPrinting in new business ventures and study entrepreneurial ideation. .

It first presents an overview of the research streams of market discovery and creation from the fields of entrepreneurship and technology management. The thesis elaborates that current frameworks for the implementation of AM that derive from the theories in entrepreneurship and technology management, interpret design as a process of search within a known solution space (Simon, 1996). This review discuses that the implementation of AM disregards the interaction with the printer and treats it as a tool for the unidirectional implementation of strategy because it conceives design as a search process. The review presents a different interpretation of cognition in design as an exploration process (Dorst & Cross, 2001). The thesis articulates that the 3D printer becomes an integral part of the development process because it facilitates the exploration of the solution space. Likewise, it provides flexibility to the incorporation of new product features and stakeholders for the exploration of the design space of the opportunity.

Based on the theory of effectuation from the creation entrepreneurship domain (Sarasvathy, 2001a), this study defines it object as entrepreneurial ideation. Entrepreneurial ideation is the process of opportunity development where a pair of product and firm ideas are created concurrently. An iterative process grounded in the theoretical and methodological frameworks was used to refine and implement two studies of the interaction of participants with complexity freedom in entrepreneurial ideation exercises. The first study introduced the entrepreneurs to a design process aided by a construction kit and a cost structure. The second study focused on a mental imagery exercise aided with images of varying complexity levels. Findings from both studies suggest that entrepreneurial ideation evolves from the determination of the basic principles that describe the affordable operation of the solution prior to the development of the product architecture. As a result, the interaction with the technological means that include the 3D printer influence the available technological principles through morphology semantics. Therefore, it is possible that the advantages of complexity freedom matter only If entrepreneurial ideation can produce complex concepts beforehand.

The thesis starts by presenting a review of the concepts within entrepreneurship and technology management, that meet in the study of AM. It continues to disentangle the design perspectives that lie within and introduces important concepts for the study of entrepreneurial ideation in firm design. The definitions used amongst these arguments are redefined to introduce the methodological stance and the study of interaction in entrepreneurial ideation. The thesis continues with the description of both studies and their results. Findings are framed back into the models within entrepreneurship, and technology management. The discussion presents insights from the study of entrepreneurship as a design process. Finally, a proposal for the further study of morphology in entrepreneurial ideation is presented.

2 Literature Review

The research described in this thesis investigates the barriers and opportunities that *Additive Manufacturing* (AM) creates in *entrepreneurial ideation*. This literature review seeks to inform from a range of relevant disciplines. Accordingly, it draws from research on entrepreneurship, technology management, 3D printing technology, and design which share terms and units of study but are seldom articulated together. The analysis in this chapter focuses on within those fields that account for design processes and identifies that their underlying assumptions of cognitive processes within design prevent their articulation. For this purpose, this chapter introduces four central concepts which can be compared as different perspectives of the implementation of 3D Printing: entrepreneurial effectuation, the mirroring of product architecture, complexity freedom in 3D Printing, and design cognition as exploration. This literature review suggests a shift in perspective that can coherently integrate these ideas to inform the study of 3D printing in entrepreneurial ideation.

The literature review is divided in three sections: an initial review and comparison of the working concepts in entrepreneurship, technology management, and additive manufacturing, an analysis of the models of design within them, and the definition of entrepreneurial ideation as exploration. The chapter closes with the definition of the problem space in the exploration of technology in entrepreneurial ideation.

2.1 Initial Theory Review and Comparison

The first section of the literature review examines overlapping themes across the fields of entrepreneurship, technology management, and AM technologies. It first defines *firm creation* and describes the two main academic perspectives that account for it. The section continues to analyse *product architecture* and the models that relate it to the structures of industries and technological cycles. The last subsection of this comparison depicts the current state of research that concerns the technological development of AM technology.

2.1.1 Entrepreneurship or firm creation.

Entrepreneurship is considered typical, yet its definition is elusive since it lays in the intersection of the micro level of social change and the organization of businesses (Davidsson, 2016) (Figure 2.1). This intersection is important for the research project because it excludes change initiatives that do not engage with the market, and small businesses that do not engage in change. Definitions of entrepreneurship range between “the creation of organizations” (Gartner, 1988), “the competitive behaviours that drive the market process”

(Kirzner, 2015), and “the Introduction of new economic activity that leads to change in the market place” (Sarasvathy, 2008).

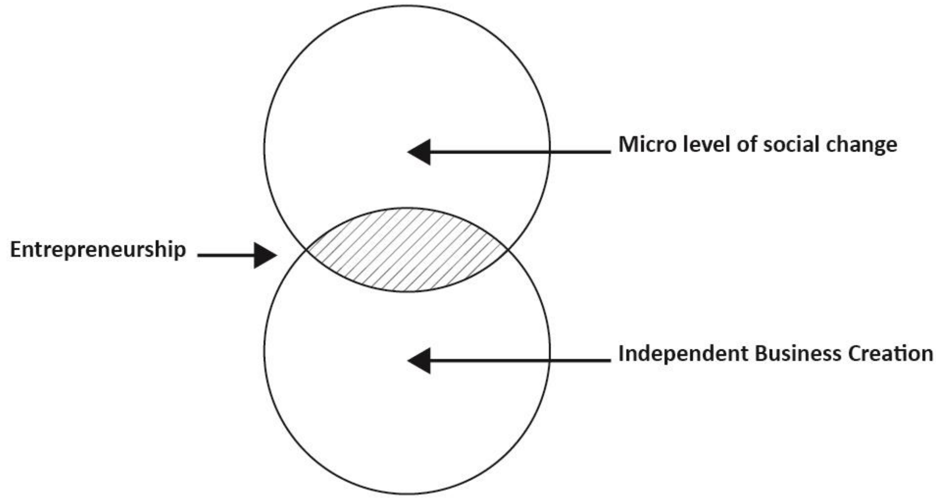


Figure 2.1 Entrepreneurship in the intersection of change and independent businesses. Adapted from Davidsson (2016).

It is consistently accepted that entrepreneurial activity powers the economy through the introduction of new products, technological means, markets, and industrial organizations (Schumpeter 2002). Accordingly, a direct relationship is assumed between the increase of entrepreneurial effort and economic growth, suggesting that modern economies should direct policies to foster innovation and reduction of barriers of entry (Muñoz & Otamendi, 2014). The focus of entrepreneurial firms, their economic output, and the return that entrepreneurs get, is different depending on contextual factors (Audretsch et al., 2001; Global Entrepreneurship Research Association, 2017; Hamilton, 2000). For the purposes of this research, the project will define entrepreneurship as the socio – economic phenomenon comprised by the micro level behaviours in charge of introducing new offers in the market, and with the purpose of changing a state of affairs (Davidsson, 2016). Hence, this thesis considers entrepreneurship a collection of behaviours implemented by the entrepreneur and their stakeholders, which include firm creation and entrepreneurial ideation.

The study of entrepreneurship originated from economics and management scholars of the twentieth century such as Frank H. Knight, Joseph A. Schumpeter, and Peter F. Drucker. The focus of entrepreneurship research has evolved from broader matters of competition, organization, and industrial analyses towards a more specific domain that includes value creation, environmental determinants of entrepreneurship, and increasingly the entrepreneurial process (Ferreira et al., 2015). However, two main themes are the most important within the field : the origins of business opportunities and the individual nature of entrepreneurs. Different assumptions of both themes give way to two main threads of entrepreneurial research.

Researchers disagree whether market opportunities pre-exist business ideation or are created by it. The market is the space through which buyers and sellers exchange goods (Sherman et al., 2008). While some researchers propose that the entrepreneurial market space is characterized by calculable risk, others indicated that this environment presents incalculable uncertainty (Alvarez & Barney, 2005). The researchers that suggest the existence of uncertain markets refer to the definition of risk and uncertainty proposed by Knight (2012). Here, risk is the unknowability of the result of an action while being able to calculate the probabilities of getting a knowable set of outcomes. On the contrary, uncertainty is the unknowability of the result of an action where both the possible outcomes and the probability of getting them are unknown. Both accounts of the nature of the market have consequences in the way the entrepreneurial process is portrayed.

The second disagreement concerns whether individual heterogeneity should be considered relevant (or irrelevant) for the discovery or creation of market opportunities. If the environment is considered risky, the individual differences in experience, skills, cognitive capacity, and motivations can be used to calculate risks and thus, matter for the discovery of the market opportunity (Shane & Venkataraman, 2000). If considered uncertain, individual differences are not relevant since any combination between environment and individual is contingent and cannot be planned forward (Sarasvathy, 2001b). Both sets of environment – individual assumptions represent two groups of teleological causation of entrepreneurial action that interpret the way entrepreneurs engage in the creation of a firm in the entrepreneurial process; *discovery* and *creation* of entrepreneurial opportunities (Alvarez & Barney, 2007). Each of them assumes a different interpretation of design cognition and is introduced in the following subsections.

2.1.2 Discovery theories of entrepreneurship.

Alvarez & Barney make an analogy between discovery theories of entrepreneurship and mountain climbing. In mountain climbing, climbers first need to select the mountain and then start climbing. The higher (valuable) a mountain is, the more difficult it is to climb. They point out that in discovery perspective of entrepreneurship, competitive imperfections that generate opportunities arise exogenously. These exogenous imperfections include consumer behaviour, technological trends, policies and regulations as well as social and demographic changes. Discovery theories assume market opportunities as pre-existing, and that individual differences are important to perceive opportunities (Alvarez & Barney, 2007). Thus, discovery theses have a naturalist view of markets. The discovery of market opportunities relies on the ability of the entrepreneur to find the location of a business venture in the socio economic landscape, and the allocation of entrepreneur's resources to exploit an existing opportunity (Bhave, 1994; Gartner, 1985).

The most representative model of this school of thought is the discovery and exploitation of market opportunities presented by Shane and Venkatamaran (2000). Within it, three categories of market opportunities are defined: the creation of information, the exploitation of market inefficiencies, and the reaction to shifts in the opportunity landscape. Entrepreneurs rely on individual differences, such as skills and cognition, in order to perceive of the misfits that surround them. Once discovered, the opportunity is evaluated in order to assess whether its nature represents an attractive return and fits the personal background of the entrepreneur. If the opportunity shows enough attractiveness, the entrepreneur shall proceed to its exploitation by creating a firm or selling the opportunity to someone else. Furr et al. (2016) propose a model of opportunity discovery, where entrepreneurs are portrayed as "empirical theorists", individuals that develop and empirically test hypotheses of value creation. Discovery theories of entrepreneurship consider that firm creation is a matter of strategic search of market opportunities of opportunities and iteration of value capture mechanisms.

The appearance of a firm from a discovery perspective is portrayed as a decision making process : *"Two major institutional arrangements for the exploitation of these opportunities exist-the creation of new firms (hierarchies) and the sale of opportunities to existing firms (markets)-but the common assumption is that most entrepreneurial activity occurs through de novo startups"* (Shane & Venkataraman, 2000, p. 224). These theories suggest that the appearance of new startups is a final step in a decision-making process once the product matches the market opportunity. Shane & Venkatamaran (2000) seem to assume that the creation of new business ventures is a process of trial and error in search of the most optimal configuration of the firm boundaries. This process experiments to find out which transactions should be included within the firm or in the market as already referred in the existing theories of the firm (Coase, 1937; Hart, 1988; Williamson, 1989).

Theories of the firm relevant for the understanding of this optimization process include the transaction cost and incomplete contracts. The theory of transaction costs posits that transactions of great specificity and uncertainty need to be controlled to optimize operational efficiency (Steven Tadelis & Oliver E. Williamson, 2012; Williamson, 1989). Therefore, transactions that have strong technological intensiveness (such as an automated process) need little or no control and can be bought in the market as commodities. On the contrary, transactions that are less technologically intensive and need more control will be tied to a hierarchy, where a coordinator (in this case the entrepreneur) can solve conflicts that disturb costs. The theory of incomplete contracts builds upon transaction cost economics to add that contracts between firms can be incomplete in the sense that they cannot predict the behaviours of all the contracted partners in the future (Hart, 1988). Change in the market creates disturbances that can affect the voids that are not covered by the given contract. Partners that possess the means to control decisions over that disturbance, will have residual rights of control. Accordingly, those residual rights of control will give that partner rights over profit. An entrepreneur will then integrate inside the firm, those assets that could be involved in incomplete contracts and gain rights over profit.

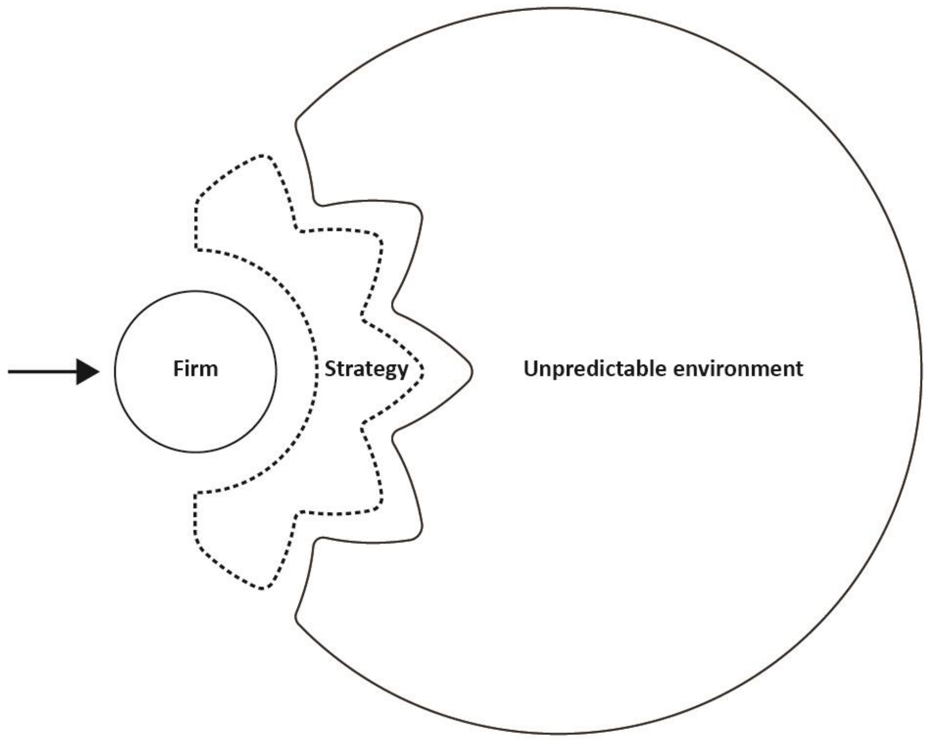


Figure 2.2. Introduction of a firm to the market through strategy. Adapted from Porter (1997).

The creation of a firm is portrayed as the search of a strategy that orchestrates resources to create a unique position in the market (Porter, 1997). Strategy fits a set of activities to sustain a competitive advantage in a risky environment. Hence, aligned to the assumptions in the discovery viewpoint, the design of strategy could be understood as the search for correspondence of the inner organization to exogenous factors (Figure 2.2). The strategies for firm creation gather information ex-ante to design and assemble the transactions and contracts that the firm needs in order to survive and compete under such unpredictable circumstances. Today the tool par excellence for firm creation is *Business Modelling* (Foss & Saebi, 2017). The business model is a representation of the resources, capabilities, and activities inside a firm and how are they orchestrated in order to achieve a sustainable competitive advantage. The template of a business model is used to determine the acquisition of assets and the deployment of activities that will comprise the firm further in the future (Zott et al., 2011; Zott & Amit, 2010).

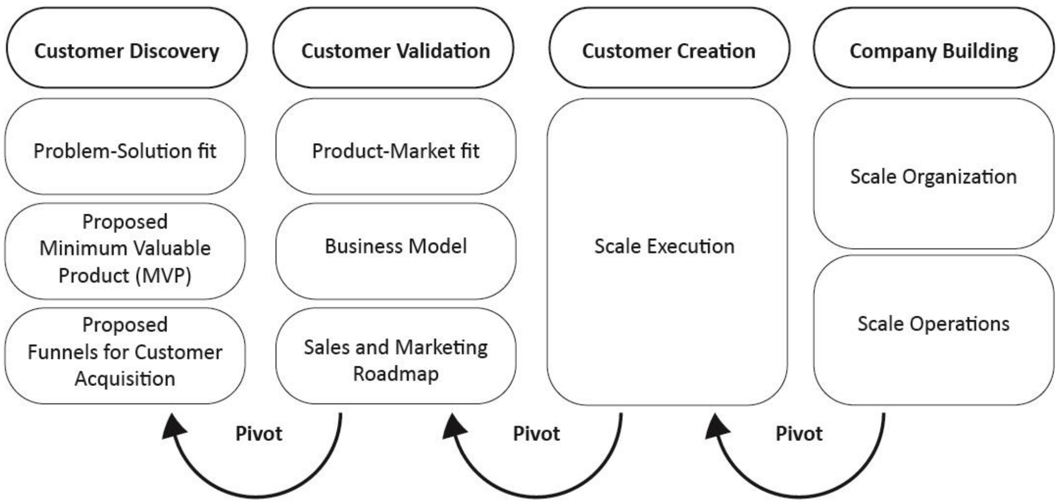


Figure 2.3. The customer development process (Cooper & Vlaskovits, 2010).

Business models are represented at different levels of specificity (Osterwalder et al., 2005). The most popular instantiation of the business model is the Business Model Ontology (Osterwalder 2004). Business model design deals with the formation of a coherent logic (value proposition, value creation, value distribution) and a profitable cost structure (Joan Magretta, 2002). The design of this logic is iterated to fit the exogenous forces in incremental steps in order to scale the operation of the firm (Cooper & Vlaskovits, 2010; Osterwalder et al., 2015; Ries, 2011). Figure 2.3 represents one of the most known methods for business model creation known as the customer development process (Cooper & Vlaskovits, 2010). The method looks for the fitness of the resources of the entrepreneur and the market opportunity by using prototyping for the reduction of risk. If unsuccessful, the method recommends to “pivot” the configuration of the current prototype until the business model and the firm fit adequately to the market opportunity. Lately, Design Thinking has influenced the development of these methods as shown in the inclusion of user-centred techniques of enquiry (for the development of the initial value proposition) and prototyping (as an effective method of iteration for fitness) (Brix & Jakobsen, 2014; Kimbell, 2011; Martin, 2009; Mueller & Thoring, 2012; Savoia, 2011). Theories of discovery portray a process of firm design where entrepreneurs generate requirements, search, and empirically test their assumptions to optimize the set of activities that will comprise the firm.

2.1.3 Market effectuation and creation theories of entrepreneurship.

If discovery premises of entrepreneurship can be compared to mountain climbing, for Alvarez & Barney (2007) creation theories of entrepreneurship are analogies of mountain making. In this context, the search process is irrelevant since opportunities are not considered pre-existent and cannot be measured in order to evaluate its fitness. Therefore, exogenous forces are not the only agents in the creation of new business opportunities. Rather, creation theories indicate that opportunities emerge through the interactions of entrepreneurs with their resources and environment. Creation theories of entrepreneurship have not been the central focus of entrepreneurial research (Ferreira et al., 2015).

Contrasting Causal and Effectual Entrepreneurial Processes

Categories of Differentiation	Causation processes	Effectuation processes
Givens	Effect is given	Only some means or tools are given
Decision-making selection criteria	Help chose between means to achieve the given effect Selection criteria based on expected return Effect dependent: Choice of means is driven by characteristics of the effect the decision maker wants to create and his or her knowledge of possible means	Help chose between possible effects that can be created with given means Selection criteria based on affordable loss or acceptable risk Actor dependent: Given specific means, choice of effect is driven by characteristics of the actor and his or her ability to discover and use contingencies
Competencies employed	Excellent at exploiting knowledge	Excellent at exploiting contingencies
Context of relevance	More ubiquitous in nature	More ubiquitous in human action
	More useful in static, linear, and independent environments	Explicit assumption of dynamic, nonlinear, and ecological environments
Nature of unknowns	Focus on the predictable aspects of an uncertain future	Focus on the controllable aspects of a predictable future
Underlying logic	To the extent we can predict future, we can control it	To the extent we can control future, we do not need to predict it
Outcomes	Market share in existent markets through competitive strategies	New markets created through alliances and other cooperative strategies

Table 2.1. Comparison between the causal logic of entrepreneurship and the effectuation logic (Sarasvathy, 2001a).

Three theories are considered here to be representative of the research stream: Entrepreneurial Bricolage, Entrepreneuring as a practice, and the theory of Effectual Entrepreneurship. Firstly, the theory of Entrepreneurial Bricolage suggests that different combinations of the same set of resources can create firm differentiation. Thus, entrepreneurs “bricolage” (making-do with what is at hand) and test the boundaries of their resources until they generate something new out of nothing (Baker & Nelson, 2005). A second theory portrays entrepreneurship as a practice of enactment of the organizing context of stakeholders and resources around the entrepreneur (Johannisson, 2011). The organizing context is the local arena, where language gives meaning to the shared practices in the interaction among the members of the network (human and non-human). Entrepreneurship with this organizing context is described as the practice of incorporation and recombination of social and cultural influences. Finally, the theory of *effectuation* questions the causal logic behind strategic design and pre-existing markets to claim that expert entrepreneurs do not rely on measurements that predict market behaviour, but rather look for control of what they have at hand. Contrary to a search process, effectuation focuses on the enactment of the contingencies (Table 2.1). The effectuation thesis observes that expert entrepreneurs preferably build partnerships that reduce the possibility of loss with people and resources that they know they can control (Sarasvathy, 2001a, 2008, 2001b). The relevance of the resources and environment in the decision-making process point out that in this proposition, the design of strategy is not a search process but interaction. Sarasvathy & Venkatamaran (2011) argue that effectual decision making is ubiquitous in human action.

In creation theories of entrepreneurship, the formation of the firm is continuously evolving. Most of the approaches in creative entrepreneurship assume that the opportunity and the firm are constructions that co-evolve through the interactions with the social environment. Therefore, firms have a path dependent development where small differences in decision-making can create great differences over time.

The theories of the firm that underlie entrepreneurship disagree with the arguments of creation because they have ontological assumptions that assume that the opportunity is knowable beforehand. Transaction cost economics implies that knowledge about the disturbances of the market is available for the entrepreneur to decide to either integrate an activity into the firm or acquire it opportunistically through the market (Steven Tadelis & Oliver E. Williamson, 2012). Likewise, incomplete contracts would define asset and return ownership according to the known residual rights (Hart, 1988). Both theories fail to account for the origins of firms when new firms confront isotropic markets where information about costs, disturbances, and expected return is not accessible (Alvarez & Barney, 2005).

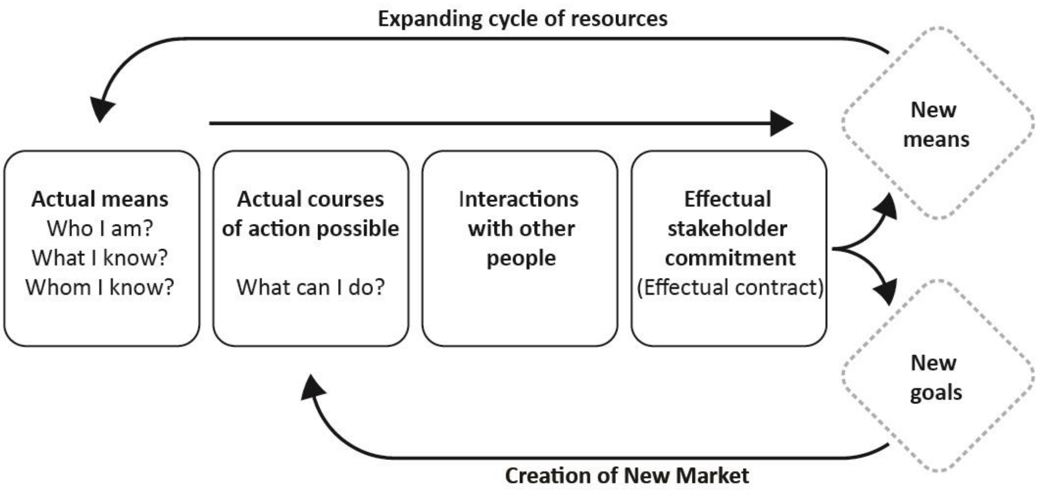


Figure 2.4. The effectuation of markets. Adapted from Sarasvathy & Dew (2005).

With the purpose of explaining the origin of the firm structure, the effectuation theory of entrepreneurship proposes interactive processes that jump between “problem” and “solution” in a fluid enactment of the environment. Feedback of the previous decisions (enactments or interactions) modifies the appreciation of the problem since the assets of the entrepreneur have already changed. Sarasvathy & Dew (2005) advocate for a model of market creation, where the stakeholders, consumers, and institutions involved in regulation and supply, shape markets. Figure 2.4 shows the process of market creation as an iterative cycle where the entrepreneur enacts the resources at hand in every instantiation of the firm. (Figure 2.4)shows, how every cycle uses the resources at hand to interact with possible stakeholders that will add new means or goals to the venture.

In this model of market creation, entrepreneurs set a personal goal and make a record of the means they have at hand (Who I am? Whom I know? What I know?). With this information, they ideate possible actions within their local stakeholder network. Interaction with the motivations and means of other stakeholders can result in commitments (otherwise referred as contracts in economics) that expand the entrepreneur's resource space by including more means or modifying the venture's goals. The acquisition of more stakeholders develops the specialization of each of them and solidifies the business opportunity. Supply chains, regulators, advocate groups, etc. are results of these stakeholder incorporations that over time become the market institutions. Sarasvathy (2008) makes an interesting analogy of the market creation process with quilting, where contrary to puzzle solving (discovery assumptions), the pieces of the quilt are acquired contingently altering the design with every incorporation added.

Very few descriptions exist that detail the specifics of opportunity creation. Nevertheless, Sarasvathy & Dew (2005) describe an illustrative example of the process of creation of entrepreneurial commitments based on the evidence drawn from protocol studies. The thought experiment considers an entrepreneur that designs gadget X with the available resources. The entrepreneur brings a gadget X to a stakeholder within her reach. The stakeholder (a retailer in this case) shows interest in the entrepreneur's offer but wants to make changes that, under her goals, would make sense. In this case a change of colour in gadget X. The interaction represents the creation of an opportunity through the negotiation between two stakeholders:

> *Let us assume Entrepreneur E brings widget X to Customer C to make a sale… Let us further assume that she wants to sell 1,000 units of X to C at $100 apiece. Let us now imagine that C says the following:*
>
> *"I will gladly buy X if only it were blue instead of green." …*
>
> *Now E has a decision to make. Should she go ahead and invest in making the widget blue (cost $10 K, say)? There are several criteria she may consider in making this decision. First, she may or may not have the $10 K needed to make the modification. Second, if she does make the*

> *modification, C may or may not buy. Third, there may or may not be other possible customers (say, D) who may be willing to pay >$100 (say, $120) per unit for a green X – i.e. for the widget as is, without any modification…*
>
> *In our current thought experiment, the strongly effectual solution takes the form of the following counter-offer to C:*
>
> *"It will cost me $10 K to make the modification you suggest. I will make the modification if you will put up the $10 K up front. In fact, if you will pay for the modification, I will even supply you the modified widget at $80 per unit, so ultimately you will end up saving money on this purchase."*
>
> *(Sarasvathy & Dew, 2005, pp. 544–546)*

Instead of trying to estimate the probability of any of the first options happening (using a causal logic as in discovery theories), the effectual entrepreneur ideates a joint strategic commitment using the product. The entrepreneur accepts the changes only if the stakeholder involves himself in the venture (in this case with an advanced payment or a long-term contract). Therefore, the commitment then creates a partnership that goes beyond the initially thought transaction expanding business opportunity. More insightful is the fact that this process links the creation of the firm to the nature of the negotiated product and posits the firm as means to achieve partnership goals.

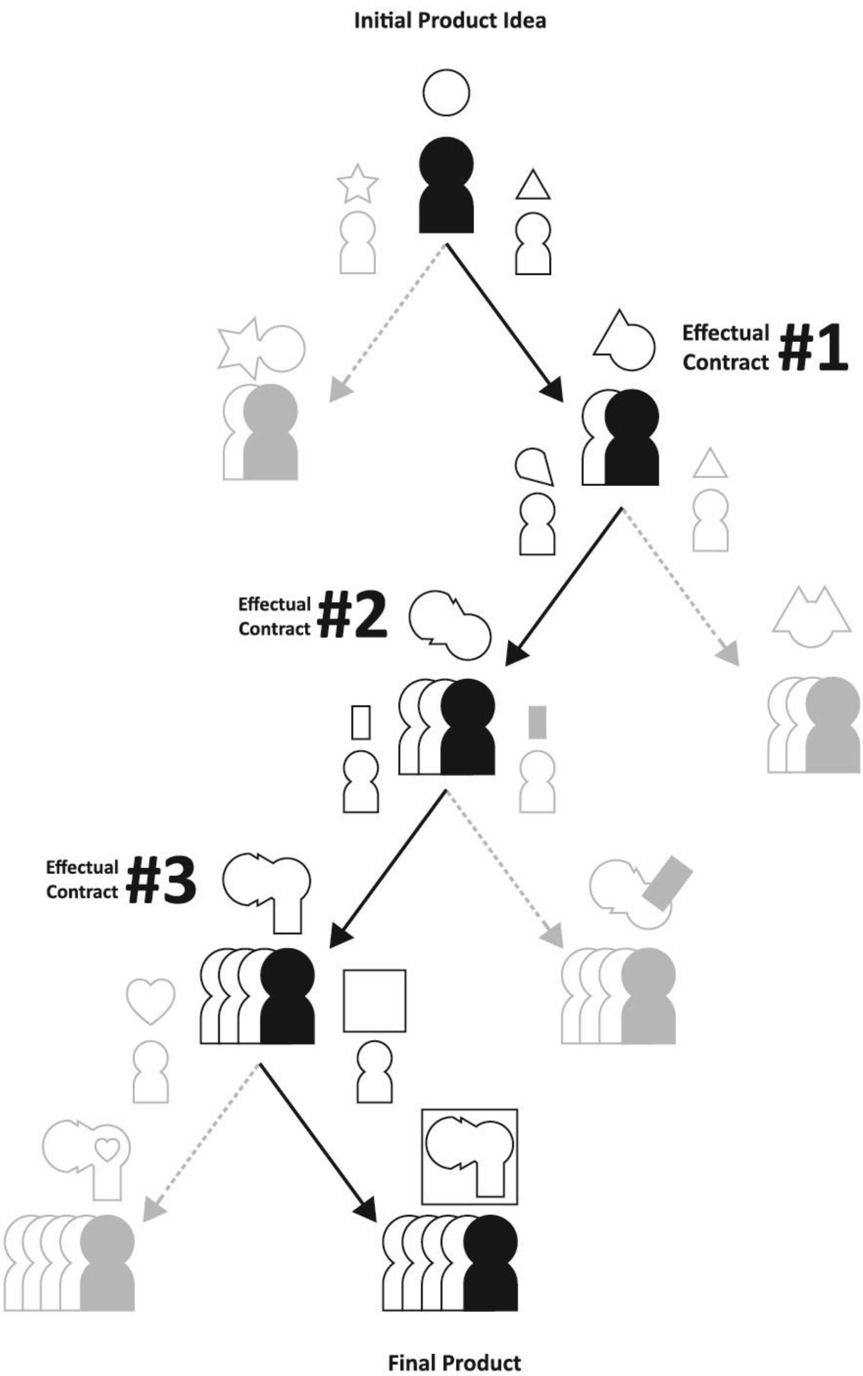


Figure 2.5. Introduction of partnerships and product configurations. Adapted from Sarasvathy & Dew (2005).

Figure 2.5 shows how the effectuation of markets looks from the perspective of the product. It is important to notice, that in every iteration of the effectuation cycle, the accumulation of interactions fixes one aspect of the configuration of the product too. Concurrently, the roles of the involved stakeholders specialize giving birth to financers, suppliers, distributors, retailers, and regulators. Therefore, the firm grows by making long-term commitments that shape certain features instead of others and give birth to categories and standards that characterize the market institutions that include, customers, competitors, regulators, and supply chains (Sarasvathy & Dew, 2005).

Sarasvathy views the firm as instrumental to the entrepreneur and not only as a collection of behaviours. Using the definition of an “artefact of design” proposed by Herbert A. Simon, Sarasvathy frames the firm as this interface that negotiates with the environment using the product Implicit in the effectual commitment, the agreements that shape the firm architecture are grounded in the interaction with the means attainable by the entrepreneur (Sarasvathy, 2004). The product is the result of the interaction between the capabilities and resources inside the firm and represents the value proposition. Thus, its features are used in the orchestration of brand touchpoints used to communicate with the effectual network of stakeholders (Abbing & van Gessel, 2008)

This relationship between the context of ideation and the product is similar to the *disclosive spaces* proposed by Spinosa et al. (1995). Like the organizing context, a disclosive space is a local set of practices that determines the artefacts in it, the activities that can be performed, and the identities that derive from them. Entrepreneurs in a disclosive space find themselves with the opportunity for organizing and coordinating the partnerships and relationships in the business opportunity (Spinosa et al., 1995). Therefore, based on the arguments of opportunity creation, it is suggested here that entrepreneurship is strongly related to the technological means through ideation. Leveraging the means at hand represents a greater opportunity for ventures that incorporate new technologies such as 3D printing.

2.1.4 Product architecture and the mirroring process.

The interactions around the product in the effectual contract match other perspectives in the study of technology management. From the analysis of industrial lifecycles, these models portrait a an alternative view of the creation of organizations. These perspectives originate from the study of the inner-workings of a technology rather than only its market related performance attributes (Rosenberg, 1969). Technology is considered a system of man-made knowledge and artefacts that performs a desired function for users. This thesis groups in this area, studies of the impact of the configuration of such knowledge and artefacts based on empirical evidence of product design and organizational structures. Herein, the complexity of technological problems has been considered of great importance for artefact evolution affecting the performance of the technological system and its scale. Hence, the study of the relationships between the configuration and complexity of artefacts and organizations is of great importance for organizational design.

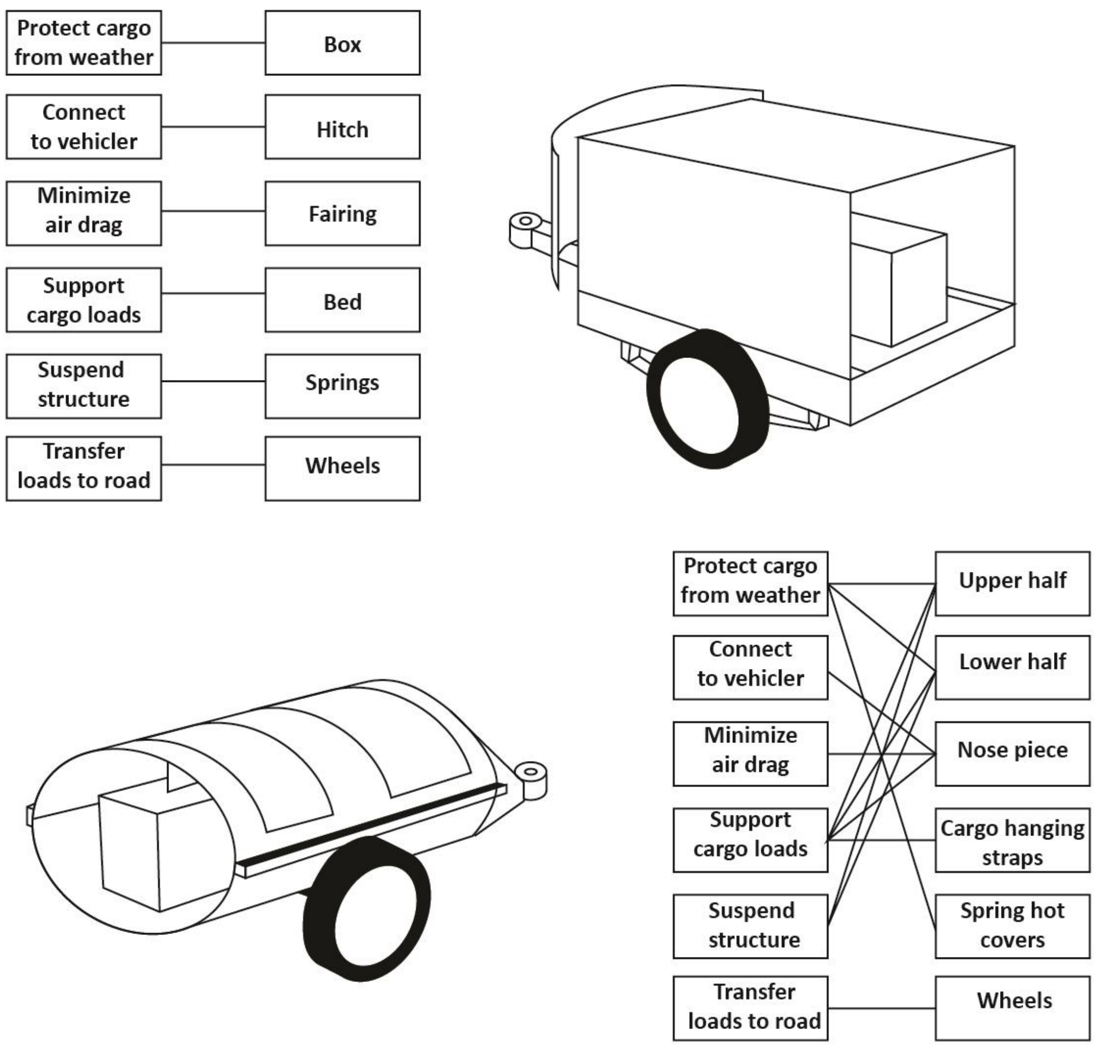


Figure 2.6. Integral (bottom) and modular(top) product architectures (Ulrich, 1995).

Studies of technological systems suggest that they are organized in a near decomposable way where interconnected subsystems include a manageable number of components, therefore creating a hierarchy of nested systems (Augier & Sarasvathy, 2004; Simon, 1996). This structure allows organizations that engage in New Product Development (NPD) arrange themselves in modules to simplify future decisions around combinations of a high number of components (Baldwin & Clark, 2000). This arrangement of functional elements to physical subsystems and components is referred as *Product Architecture* (Ulrich, 1995). In NPD, the configuration of product architecture determines the relationships between functional requirements, components, and the interfaces between them. Integral architectures feature complex mappings between functional requirements and components. In integral architectures, a component may be related to many functions of the artefact, and one function can be related to many components. In contrast, modular architectures have simpler mappings of one-to-one relations which makes them easy to separate in modules. Figure 2.6 shows the differences between integral and modular architectures of a cargo trailer. As shown in Figure 2.6, the interfaces between components in integral architectures are *coupled*, where the parts or subsystems that have a common function create interdependencies. De-coupled interfaces, more common in modular architectures, do not create interdependencies. This means that changes in the configuration of a coupled interface requires changes in both components while a de-coupled one does not.

The description of particular product architectures is situated at the level of aggregation that the categorization of its technological principles allows. Murmann & Frenken (2006) describe a principle that defines the affordable operation of the artefact and defines the limits between technologies in the study of product architectures. Despite different artefacts can solve similar functional requirements, different operational principles will create different categories of product architectures (e.g. airplanes and helicopters).

The interconnectedness of the product architecture impacts the organizational capacity for product change or standardization, product variety and flexibility, and product performance (Baldwin & Clark, 2000; Ulrich, 1995). The accumulation of routines creates an organizational memory that maintains experience, rules, procedures, beliefs, technologies and culture inside the organization regardless personnel turnover (Levitt & March, 1988; Simon, 1991). In the initial stages of the product design process, the perception of the problem is believed to determine the allocation of the design effort and create organizational routines. Therefore the subdivision of the problem will determine the interfaces that, inside the organization, represent the coordination of the design solutions (Conway, 1968). If the thesis of effectuation is situated inside the discussion of product architecture, changes in the value proposition that are available for the entrepreneur to negotiate with stakeholders are limited by the chosen product architecture.

Findings in complex product architectures show that the interdependencies of components in a Design Interface Matrix, match with high accuracy the interaction between teams (M. E. Sosa et al., 2004). Learning processes within the organization change because of the arrangement of such interdependencies. For instance, the conceptualization of integral product architectures creates sequential learning in NPD processes because they present coupled interfaces that require the understanding of core solutions first in order to accommodate peripheral components to them. In contrast, modular solutions create opportunities for standardization of interfaces, concurrent problem solving, and organizational learning (Novak & Eppinger, 2001; Sanchez & Mahoney, 1996).

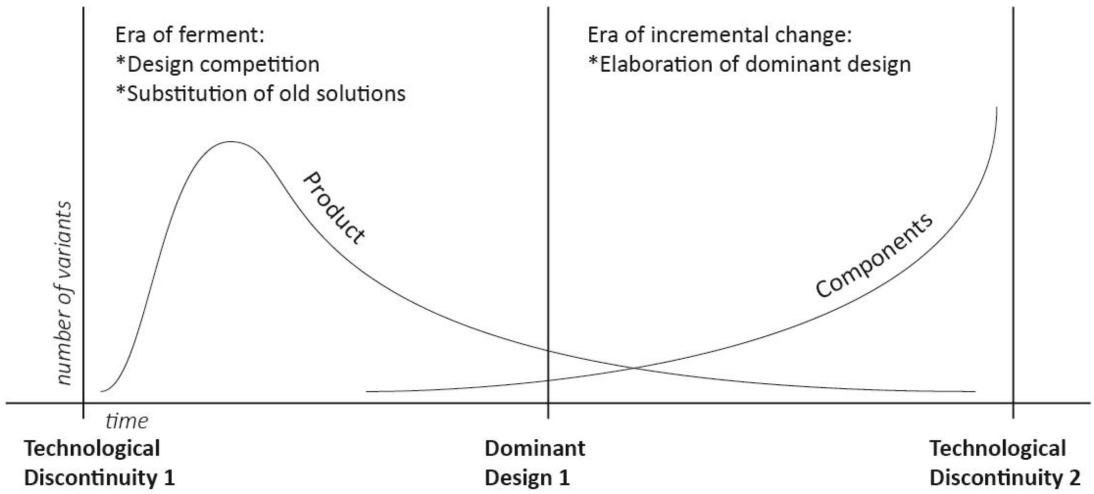


Figure 2.7. The technology cycle of product architecture (P. Anderson & Tushman, 1990).

Knowledge in an NPD process has been studied as knowledge of the components and knowledge of how components fit in the product architecture. Architectural knowledge is related to the coordination of the organization and as a result, it is also related to the ability of the organization to innovate (Henderson & Clark, 1990). The introduction of new technologies first develops architectural knowledge to later shift to the development of component knowledge. The introduction of new architectural knowledge renders existing product-organization configurations irrelevant when they cannot modify their learning processes (C. Christensen, 2013; Henderson & Clark, 1990). Anderson & Tushman (1990) introduce a model of technological change (Figure 2.7) where new entrants in a nascent industry introduce mainly architectural innovations with the purpose of solving a functional requirement that has not yet being solved by existing actors. As the market grows and the value of the requirement within the market is diffused. New entrants are pulled into the market bringing different product architectures with them. After the market tests the available products in this *ferment* period, a dominant design emerges. Such dominant design exists when the great majority of designs within a technological class have the same configuration of core components. A dominant design is a configuration of core components that controls a high number of phenotypical features of the product architecture and is successful in the market (Murmann & Frenken, 2006). Subsequent to the emergence of the dominant design, design efforts shift from core components to the peripheral leading to an era of incremental change.

In early stages the first architectural innovations, or technological discontinuities, are made of off-the-shelf components and never become the dominant design (C. Christensen, 2013). Subsequent changes to product architecture focus more in incremental innovation from the incumbent actors of the industry. The second stage of competence-enhancing discontinuities focuses in lower levels of the nested hierarchy of the product while competence-destroying ones lunge against upper levels or subsystems of the product architecture. It is argued that the crystallization of the dominant design fixes the perception of a performance dimension of the product architecture (C. M. Christensen & Rosenbloom, 1995). The causality between dominant designs and market change is debated. It is argued that a mixture of demand, economies of scale, strategies, and network externalities push the development of dominant designs (Murmann & Frenken, 2006).

The cycles of ferment and incremental change portrait technological and market change as a sequential process that propagates form the design of the product architecture. Evidence of the development sequence from core to periphery components has been found through the study of patents (Huenteler et al., 2016). This analysis makes use of patent analysis to show that just as the architectural and organizational configurations, the knowledge in technological change happens in steps. The process always incorporates existing knowledge from other domains in the creation of a radical new body of knowledge to later focus on the incremental development of the periphery of such domain.

The impact of product architecture in the organizational learning process can be articulated with the creation of markets in three ways. First, in the screening of possible stakeholders, and according to product architecture restrictions, the entrepreneur shall look for those that match the initial problem subdivision. Second, when an initial product configuration is being negotiated with stakeholders, the consequences of the negotiation shall determine a new configuration of the interfaces and their coordination where some features change while some others are fixed. Finally, the effectuation of the architecture is flexible from the start since there are no invested assets that obey specific product architecture configurations and no coordination channels fixed amongst the stakeholders involved.

Industry dynamics and the creation of markets.

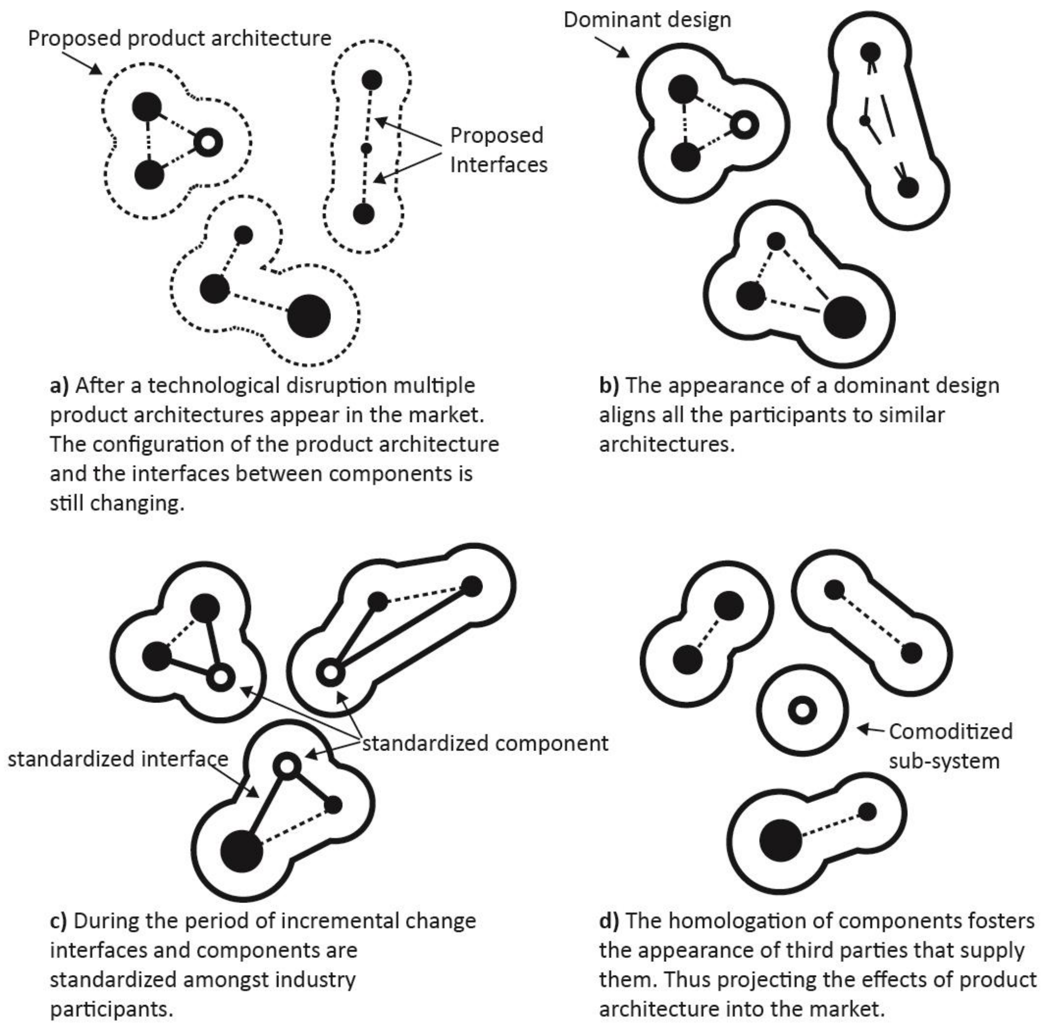
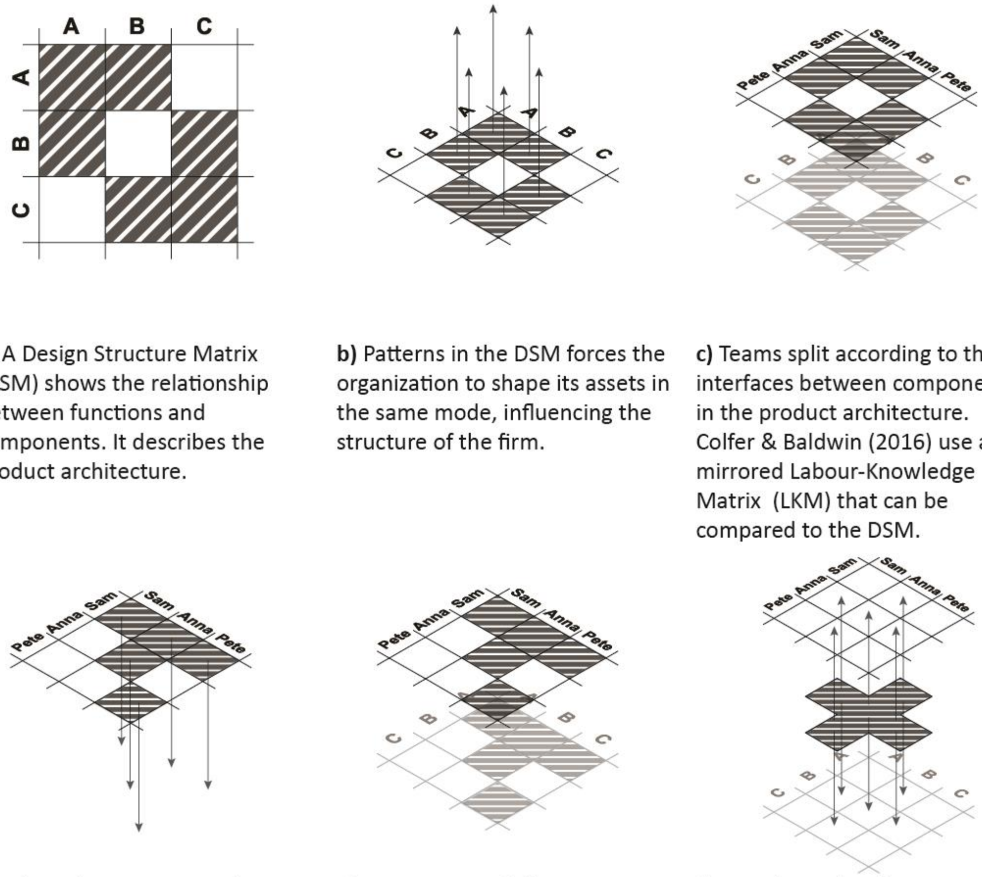


Figure 2.8 The mirroring process of product architecture. Adapted from Colfer & Baldwin, (2016).

The effects of product architecture have more consequences in the structure of institutions (Figure 2.8). Technological discontinuities are introduced by entrepreneurs with innovative product architectures without certainty of the future of the industry. Initial configurations with off-the-shelf components drawn from other technologies are assembled for the first time in custom-like integral configurations. Those integral configurations represent uncertain transactions that are been tested in the market. Hence, the initial entrepreneur is forced to keep inside the firm all the activities related to the new architectural interfaces in order to manage organizational learning and standardization (Hart, 1988; Williamson, 1989). The materialization of a dominant design fixes certain transaction costs and interfaces for the development of modular components. With the standardization of such components, their transaction costs are also structured to the point that they become predictable. Moreover, predictable transactions become industry standards aligned with the technological trajectory and its performance dimensions. With standards that control the expected transactions, there is no need to keep the related activities under the control of the firm. Instead, modules can be outsourced to supply partners that respect standardized norms and interfaces. Supply chains are therefore developed and regulators enforce the industrial norms all aligned to the perception of performance amongst the stakeholders (Colfer & Baldwin, 2016). Figure 2.8 demonstrates the *mirroring effect* that product architecture has over the structure of market institutions from problem, to product architecture, to organization, to standards, to other stakeholder organizations (Colfer & Baldwin, 2016). The *mirroring process* shows how industries change efforts according to the maturity of the product architecture and how these technological changes can be mapped to changes in the market institutions in a parallel perspective to the effectuation of markets described in the Market effectuation and creation theories of entrepreneurship. It is argued that the network of stakeholders that shares the perception of the performance dimension works as a value network of incumbent organizations (C. M. Christensen & Rosenbloom, 1995)

Dominant design research seeks to describe market creation by matching macro changes in industry dynamics with corresponding configurations in product architecture. Under traditional perspectives of entrepreneurial opportunity discovery, this means that developing understanding of the architectural environment of the technological domain will allow the prediction of the industry behaviour and organizational configurations that are possible within that environment. However, under the logic of creation entrepreneurship, technology management have a different meaning since opportunities can be built through the association of actors through the manipulation of the product architecture. This shows how the creation of opportunities can be understood as profoundly grounded in product architecture. Through the first delineation of the problem boundaries, the entrepreneur can draw the blueprint for affordable partnerships, knowledge domains, organizational learning strategies, asset acquisition, scope of design spaces, and a possible performance dimension. The iteration of the value proposition is not focused on the prediction and adjustment, but rather on the combination of knowledge brought by two stakeholders to the design space and the negotiation of the product configuration that directs the firm towards the attainment of each stakeholder’s goals.



a) A Design Structure Matrix (DSM) shows the relationship between functions and components. It describes the product architecture.

b) Patterns in the DSM forces the organization to shape its assets in the same mode, influencing the structure of the firm.

c) Teams split according to the interfaces between components in the product architecture. Colfer & Baldwin (2016) use a mirrored Labour-Knowledge Matrix (LKM) that can be compared to the DSM.

d) When the organization has been solidified by the product, the interfaces within the design team influence the available interfaces of products.

e) Organizations fall in a mirroring trap when the interfaces in the DSM and LKM block the develpment of new product architectures.

f) Complexity freedom in AM implies that relationships between functions and components can be transformed in both ways.

Figure 2.9. The effects of the interdependencies of components frame the way the organization communicates and addresses NPD. Adapted from Colfer & Baldwin (2016).

This thesis suggest that opportunities exist for the entrepreneur to intentionally leverage product architecture from the perspective of creation entrepreneurship (Figure 2.9). The plasticity of the resources that create the product architecture is important to handle new combinations especially when those resources fix long term decisions such as manufacturing processes. The emergence of digital fabrication technologies such as 3D printing has brought greater flexibility to manufacturing ventures. It is the purpose of this research to evaluate this technology as means for the effectuation of product architecture.

2.1.5 From 3D printing to complexity free Manufacturing.

Today manufacturing technologies are being transformed by digital information systems. This has led to the transformation of competitive strategies from resource management to the development of capabilities that leverage brand, product delivery, and user experience. Therefore, creating competitiveness in the development of a manufacturing related venture requires an advanced manufacturing approach that incorporates how physical and digital dimensions of production are merging (World Economic Forum, 2014). Among the technologies that can enable the creation of valuable manufacturing capabilities, 3D printing is of great interest due to its increasing impact across the value chain. Despite being over 30 years old, 3D printing is still being adopted across industries. Adoption estimates in 2014 suggested that over 60% of manufacturing corporations had experience with the technology (mostly in prototyping) while 9% of those used it as a process for manufacturing final products (PricewaterhouseCoopers LLP, 2014). Most of the early adopter examples include aerospace, electronics, and automotive industries concentrated in North American and European markets (World Economic Forum, 2017). As part of the multidisciplinary frame of this thesis, this section details the principles behind Additive Manufacturing technologies.

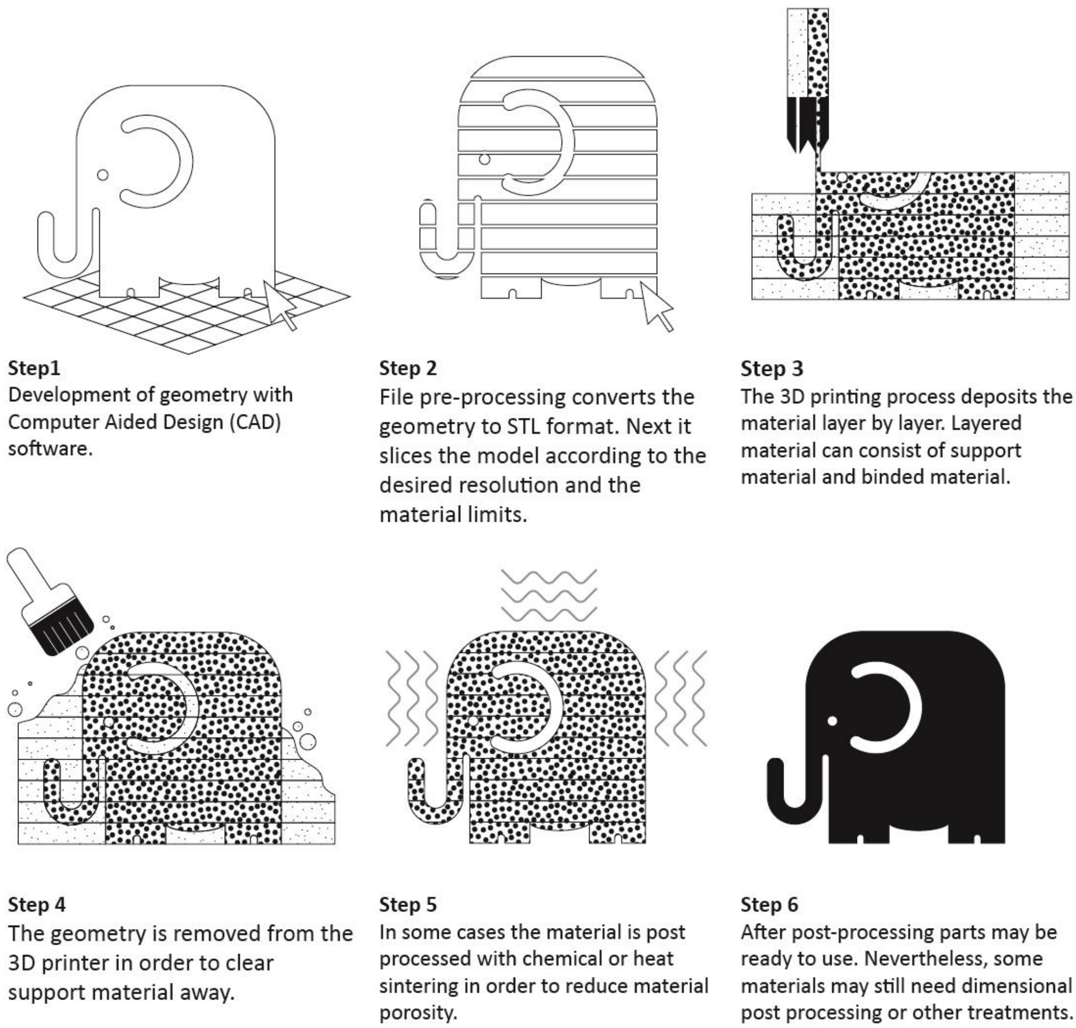


Figure 2.10. The 3D Printing Process (D. I. Gibson et al., 2010a).

The process of 3D printing differs from traditional fabrication processes because it changes the logic in the creation of volumes from the subtraction to the addition of raw material.

Traditional subtractive processes use external tools to remove material according to specifications until the final shape is achieved. In contrast, 3D printing uses Computerized Numerical Control (CNC) technology to add material only where it is needed. Figure 2.10 presents a general 3D printing process. First, after the geometry has been finished digitally (Step1), the process requires the "slicing" of the 3D model to be produced in a step known as pre-processing (Step 2). Next, the deposition system places each of the slices using a layer of material in liquid, powder or laminated form (Step 3). Each layer is joined by the application of energy (UV light, laser, electron beam, etc.) or injection of a binder. The process is repeated continuously until the form is completed. Despite some of the processes can fabricate ready-to-use parts most of them require post processing with the removal of support material or dimensional adjustment (steps 4, 5 and 6).

Initially implemented on photo-hardening polymers in 1984 (Kodama, 1981), the methods for material deposition have evolved to cover different applications (Gao et al., 2015; D. I. Gibson et al., 2010b) (Figure 2.11). Materials vary from plastics and polymers to ceramics, metals, and even biomaterials (Dan Leordean et al., 2015; Schubert et al., 2013). The extrusion of molten plastic or Fusion Deposition Modelling (FDM) stands out as the most popular process being used in consumer-ready desktop 3D printers due to the expiration of the patents in 2009 (Makerbot, 2018; Prusa Research, 2018; RepRapWiki, 2018). 3D printing technologies have been used primarily to create functional prototypes. However, through improvements in speed, cost, and accuracy it has been increasingly used to produce larger batches consequently turning into *Additive Manufacturing* (AM).

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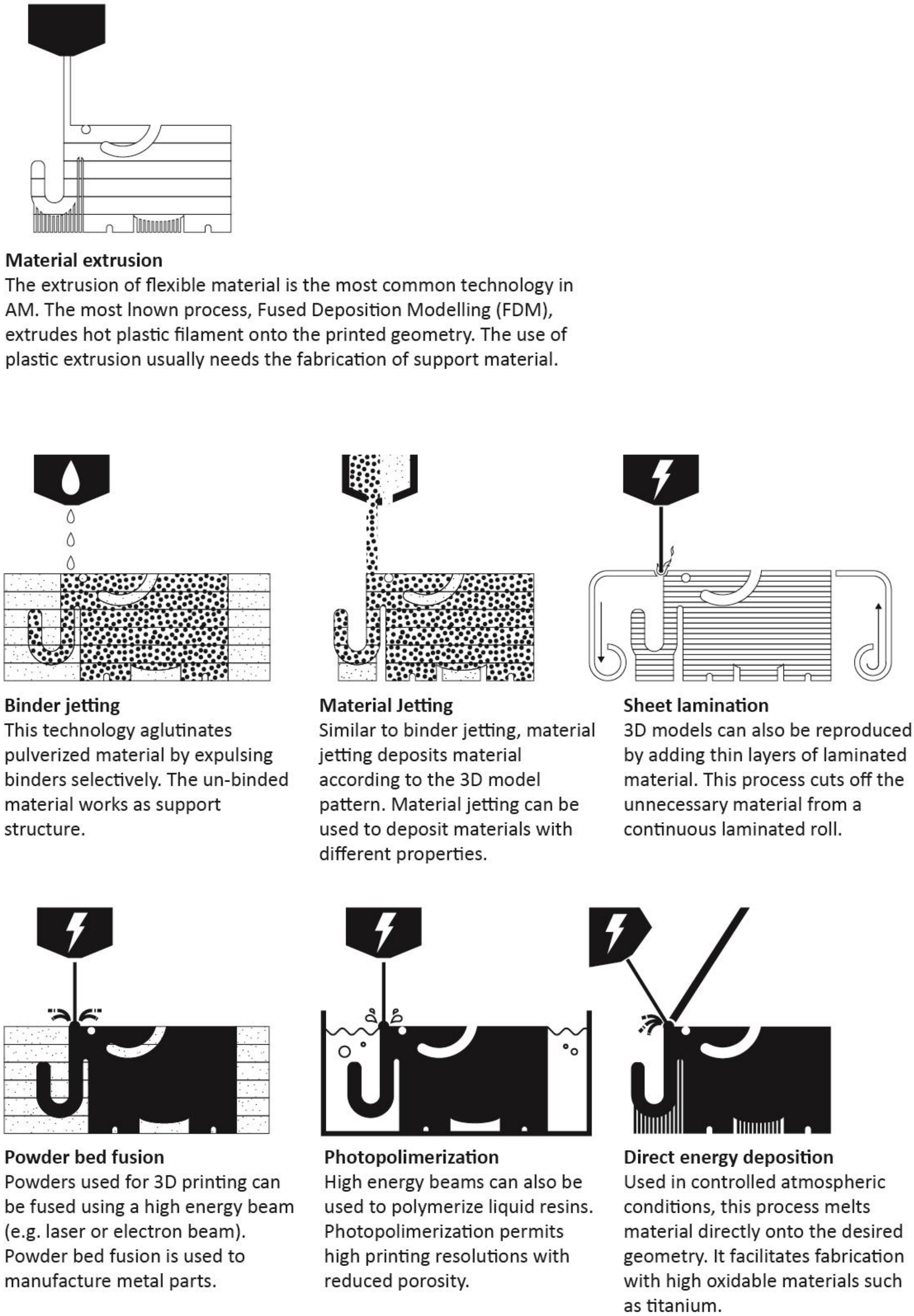


Figure 2.11. AM technologies (Gibson et al., 2010a).

Complexity freedom in AM.

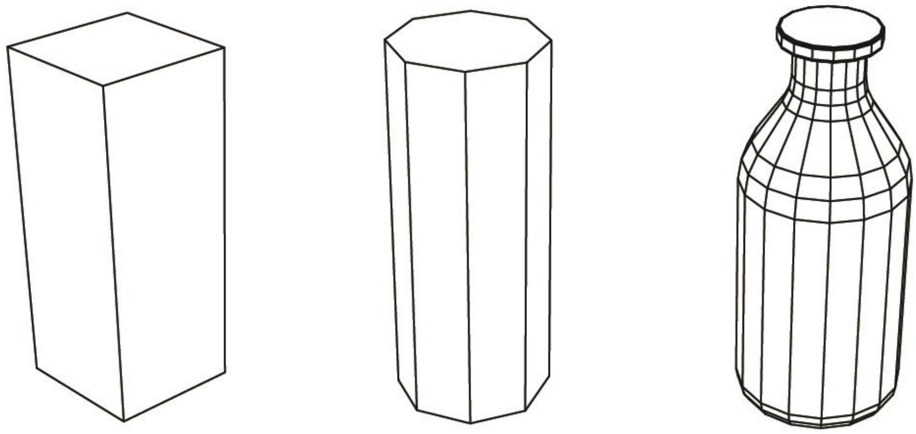


Figure 2.12. Subtractive fabrication needs more steps as the product develops more features.

Since the first industrial revolution, competition dynamics of manufacturing ventures have been dependent on the costs incurred in the fabrication of tools for production. Here competitiveness resides in the firm that produces better quality products with lower costs. The development of advantages in traditional manufacturing depends on the capacity of tools to build economies of scale. This means that the production of high volumes reduces the associated impact of fixed costs (that includes tooling) in the average unit cost. Variations in the design of products and complex geometries are not efficient since they require tool changes or modifications that increase such fixed costs (Figure 2.12). Firm differentiation is achieved by creating either high production volumes of standardized products or low volumes of complex ones. These *economies of scale* pushed the development of current global value chains where sequential activities look for the optimization of fixed costs.

Alternatively, AM makes *economies of one* available (Petrick & Simpson, 2013). The ability to deposit only the material that is needed in the final geometry eliminates the need for tooling and therefore allows the reduction of production costs to material, and energy. In AM the fabrication of a cube and a reproduction of a renaissance sculpture have the same cost as long as they require the same amount of material. In “economies of one” variation in products does not incur in extra costs, hence the cost of increasing the complexity of a geometry is “free”.

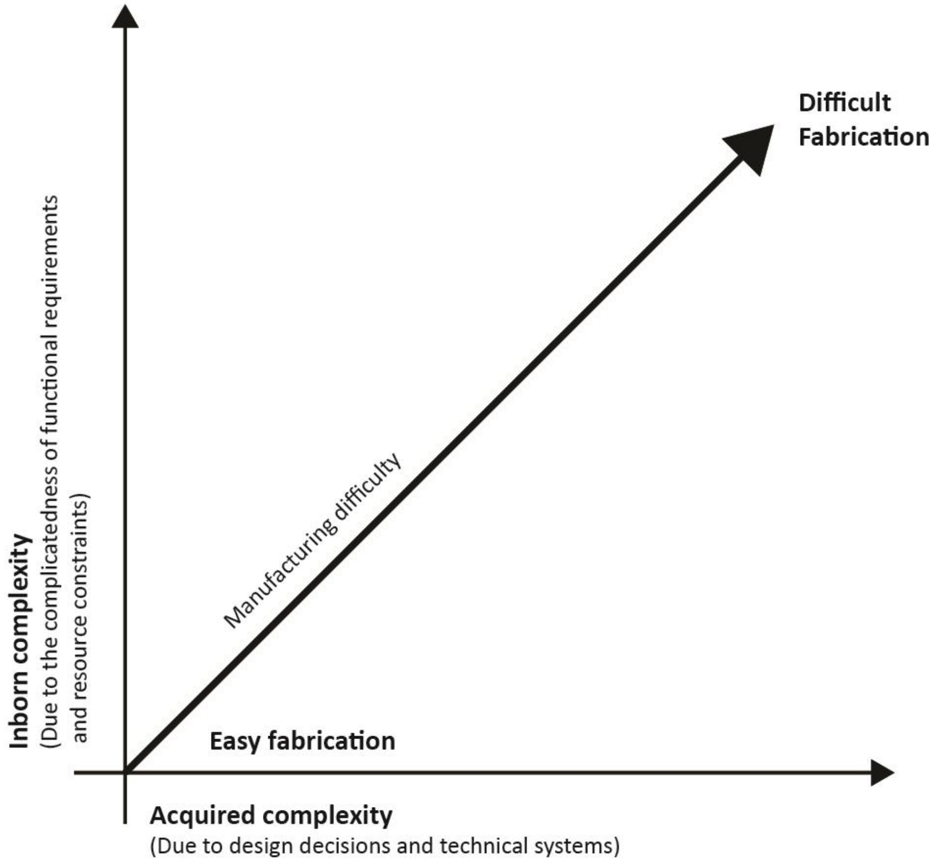


Figure 2.13. Manufacturing difficulty and complexities. Adapted from Lu and Su (2009)

Complexity in fabrication is defined as the measure of uncertainty in achieving the artefacts functional requirements (S. C.-Y. Lu & Suh, 2009). It is the result of the sum of two problem space dimensions that increase the uncertainty in the fulfilment of such functional requirements. These two dimensions, inborn and acquired complexity (Figure 2.13) add up to the overall difficulty in the product manufacturing. *Inborn* complexity is the nuisance present in the product due to the number of functions and relationships amongst them. On the contrary, fabrication processes add *acquired* complexity to the product architecture because they add elements and modifications to the product architecture in order for the manufacturing process to work (S. C.-Y. Lu & Suh, 2009). *Complexity freedom* in 3D printing refers to the availability of increased inborn complexity without the restrictions of acquired complexity. Complexity freedom can support more intricate product architectures that may introduce innovative solutions by addressing complex functional requirements.

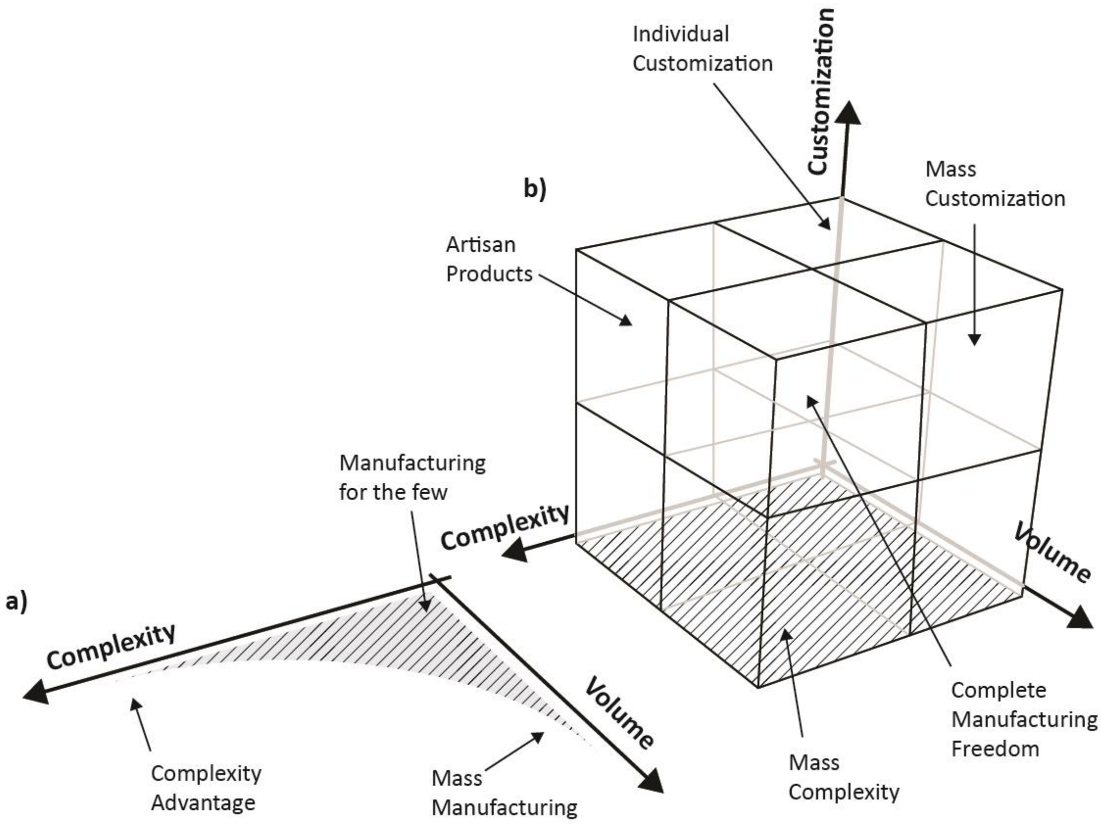


Figure 2.14. a) Traditional strategies of differentiation. b) New scenarios for competitive positioning with AM. Adapted from Conner (2014).

Complexity freedom breaks the dynamics of competition of economies of scale by adding a new dimension of product customization (Conner et al., 2014). While complexity only deals with the relationships between features contained in a product architecture, customization deals with its uniqueness. The intersection of the three dimensions creates a landscape with eight possible combinations of complexity, customization, and production volume that provide different sources of differentiation. Figure 2.14 shows a comparison between the former logic of economies of scale and the new space that is created through the introduction of AM. In traditional manufacturing scenarios, strategies for the design of product architectures were bounded by a trade-off between acquired complexity and the affordable production volume. With the introduction of AM, the combinations between complexity, production volume, and customization do not restrict each other. Traditional strategies comprised: artisanal production (low volume, high complexity, high customization), low volume production of highly complex products, and mass manufacturing. The AM landscape introduces spaces for: individual and mass customization, low and mass production of complex architectures, and manufacturing of low volumes of traditional products. Despite being accessible through AM, the combination of high complexity, high customization and high volume (complete manufacturing freedom) is difficult to imagine since there is no current example that exemplifies the mass production of a highly complex and customizable product.

The increased flexibility of product configurations in AM blurs the line between design, manufacturing, and delivering stages of the value chain. Product design expands its scope and overlaps the other two stages in a production mode that allows fast in-situ modifications, immediate fabrication, and direct interaction between the designer and the consumer. Consequently, in the implementation of AM, design represents the main in-house capability (Petrick & Simpson, 2013). Therefore, new possibilities for strategic differentiations can be created through the combination of complexity freedom and design in ways not accessible through traditional manufacturing processes.

Economics of AM.

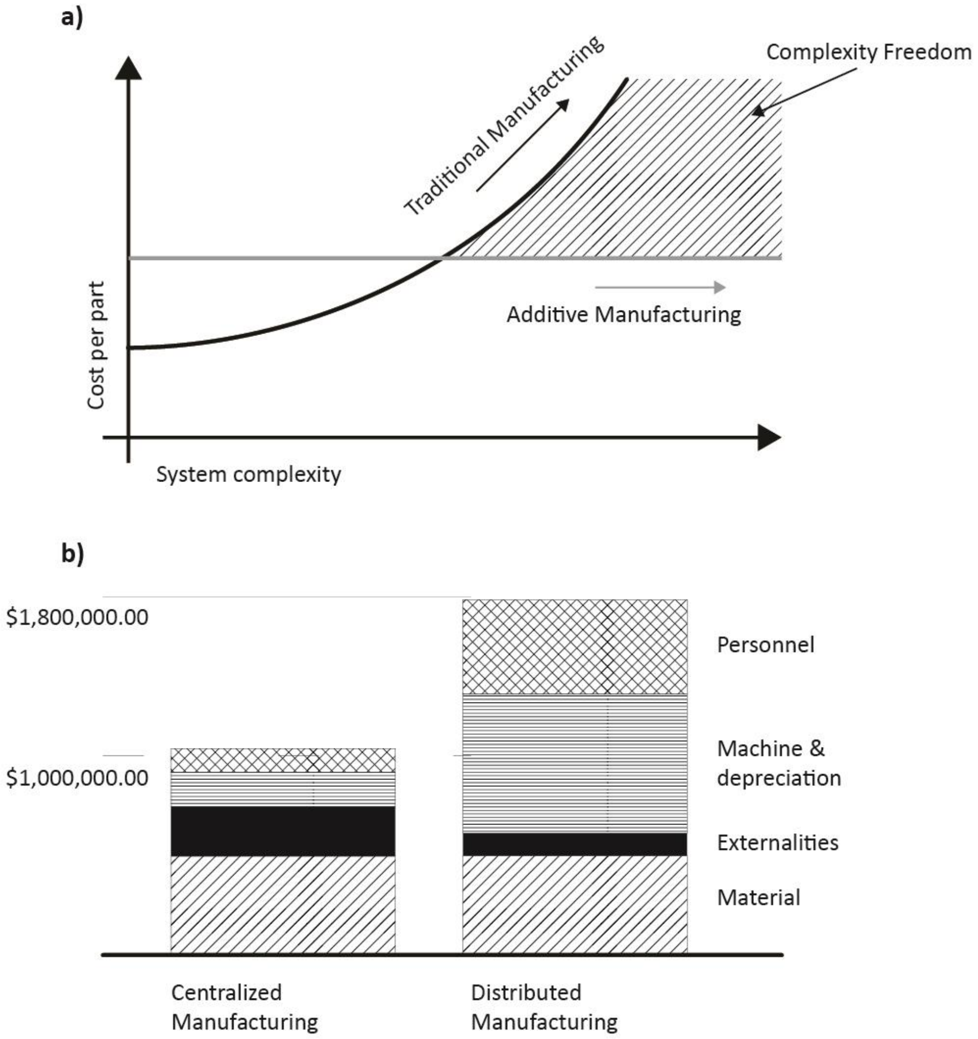


Figure 2.15. a) Complexity threshold. b) Relevance of machinery and personnel cost. (Adapted from Thomas, 2015) .

The economic benefits of AM can be classified in two main categories: expected value and diffusion, and the measurement of costs and benefits of the technology (D. Thomas, 2015). First, the real percentage of industry that uses AM for final products was estimated to be between 2% and 9% despite the fact that up to 60% of manufacturing businesses have had contact with it (Andreas Muller & Stefana Karevska, 2016; PricewaterhouseCoopers LLP, 2014). Additionally, the sales from products and services in AM has increased from $4.1 billion USD in 2014 to $7.3 billion USD in 2017 (TJ McCue, 2018). The percentage of manufacturers that use the technology and the size of the industry cannot be compared to other more mature technologies but show that the diffusion of 3D printing is progressing. Second, the cost and benefits of the technology can be further classified in comparison with traditional manufacturing technologies, and the impact on the value chain. The comparisons between subtractive and additive processes requires that the studied geometries are manufacturable in both procedures. Therefore, studies that compare both technologies use examples of aerospace and automotive industries. Results of these studies find low breakeven points where AM is feasible for production instead of traditional manufacturing of highly complex products (Figure 2.15). Hence, they recommend its use for spare part fabrication for highly specialized markets such as aerospace and military (Allen, 2006; Atzeni & Salmi, 2012; Christian Lindemann et al., 2015). Additional to comparisons, findings in the analysis within AM show that the average unit cost is mainly dependent on the cost of the machinery itself (complemented by labour, energy and material) and the way the printing volume is used (Baumers, 2012; Baumers et al., 2016).Savings in “ill-structured” costs (e.g. delivery time and storage space) throughout the value chain are possible since AM distributed sites can permit the fabrication of pre-assembled or merged components saving transportation, storage and environmental costs (Le Bourhis et al., 2014; D. Thomas, 2015). However, the projection of distributed manufacturing scenarios still suggests that efficient distributed manufacturing depends on the future assimilation of the technology which would reduce the high costs of machinery and specialized design labour (Khajavi et al., 2014).

Business modelling and AM.

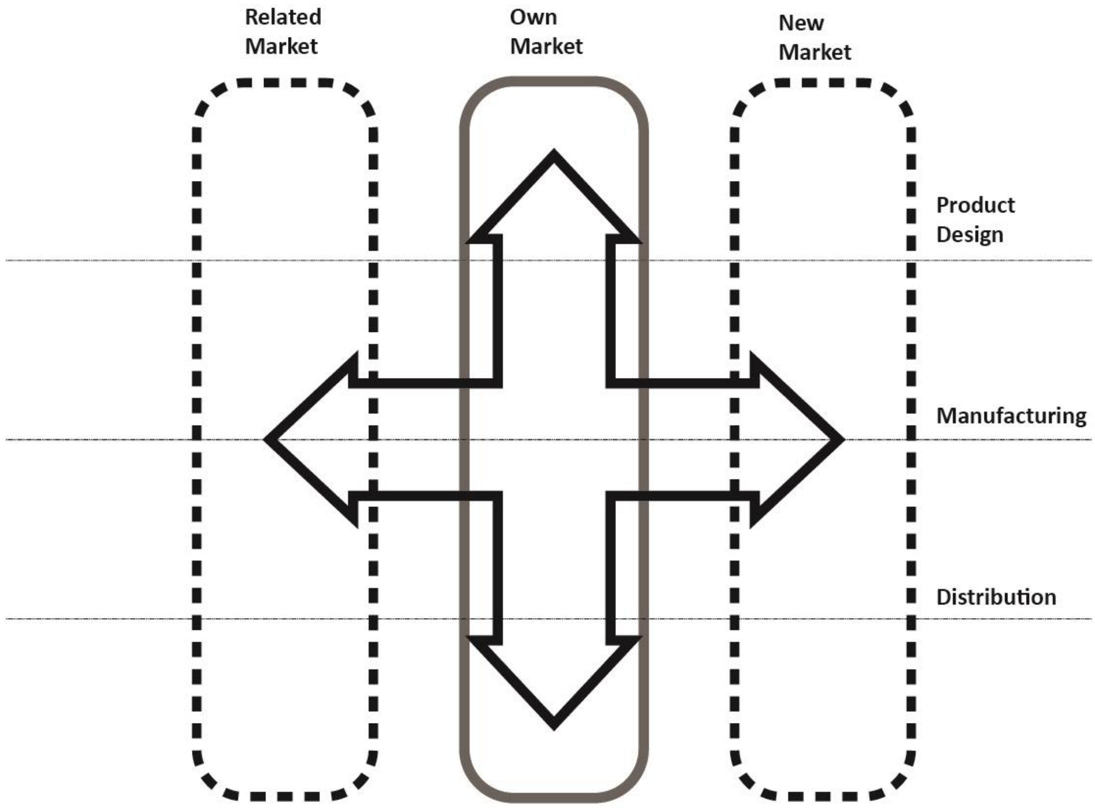


Figure 2.16. The flexibility of business modelling with AM. Adapted from Rayna & Striukova (2016).

The new dynamics of competition create interesting strategic configurations of new firms through the overlap of design, fabrication, and distribution stages. From a corporate perspective, the advantages of 3D printing influence the product and the structure of the value chain as a process. Particular opportunities can be found in the reshoring of component production in high margin industries, production of spare parts for in-house consumption, the development of long-tail strategies, or supply of unattended or abandoned industries (Andreas Muller & Stefana Karevska, 2016; Joyce, 2014; Reinhard Geissbauer et al., 2017). According to the competitive environment constraints, entrepreneurs can afford a mobile business model where the manufacturing assets adapt to strategies that are constantly changing to cover complementary adjacent markets via the modification or redesign of the core product. The business model can also integrate components vertically at will through the incorporation of assemblies or the fusion of parts that complement the value proposition making a two-dimensional flexibility (Rayna & Striukova, 2016) (Figure 2.16).

Strategic implementation of AM can happen at different levels of the business model (Rayna & Striukova, 2016). Initial integration of AM permits the acceleration of product development cycles done with rapid prototyping. The reduction of development times creates an opportunity to acquire innovation capabilities based on experimentation and opens strategic pathways. Further integration of the processes creates the possibility of rapid tooling, which broadens the flexibility of traditional manufacturing methods. Advanced integration allows direct fabrication with total reconfigurations of the product and the possibility of manufacturing at the point of purchase. A complete integration exposes the strategy to open models where networks of stakeholders can get involved in different degrees from co-design to co-retail and co-production. Examples gather crowdsourcing, open design shops, marketplaces, and home fabrication (Cautela et al., 2014; S. Fox & Stucker, 2009; D. I. Gibson et al., 2010b).

Design for Additive Manufacturing (DFAM).

The relevance of design in entrepreneurship with AM facilitates the incorporation of many levels of geometry complexity to strategy. If an entrepreneur is able to leverage complexity freedom, the creation of differentiation strategies can be supported by features in the product in structural, functional, or systemic levels. Through complexity freedom AM draws a spectrum of architectural complexity that starts with the minimal layer thickness that a particular printer can lay. A wide range of thicknesses are available being 0.1 mm a common parameter for consumer level FDM. Studies of DFAM focused on geometry design offer great opportunities for the creation of even micro-structural configurations based on the minimal resolution available (Oxman, 2010). AM can produce continuous component profiles at a micro structural level without causing fractures done in subtractive processes (Hague et al., 2004). Yet, at this micro-structural level the mechanisms of layering create a porous contact points between layers that become structurally weak. Additionally, the development of extrudable plastics used in AM still does not match the performance of injection moulding materials. Resistance to high temperatures and humid conditions is important for global markets thus restricting the use of FDM plastics for exports. The inclusion of multi-material components at the micro structural level also brings new challenges in the incorporation of different structural properties and the binding of different materials (D. I. Gibson et al., 2010c; Hague et al., 2004; Vaezi et al., 2013). Material development has a great industry interest from technology suppliers evident in the evolution of published research. Hence, it is expected that challenges in material science will generate interesting solutions for commercial purposes (PricewaterhouseCoopers LLP, 2014).

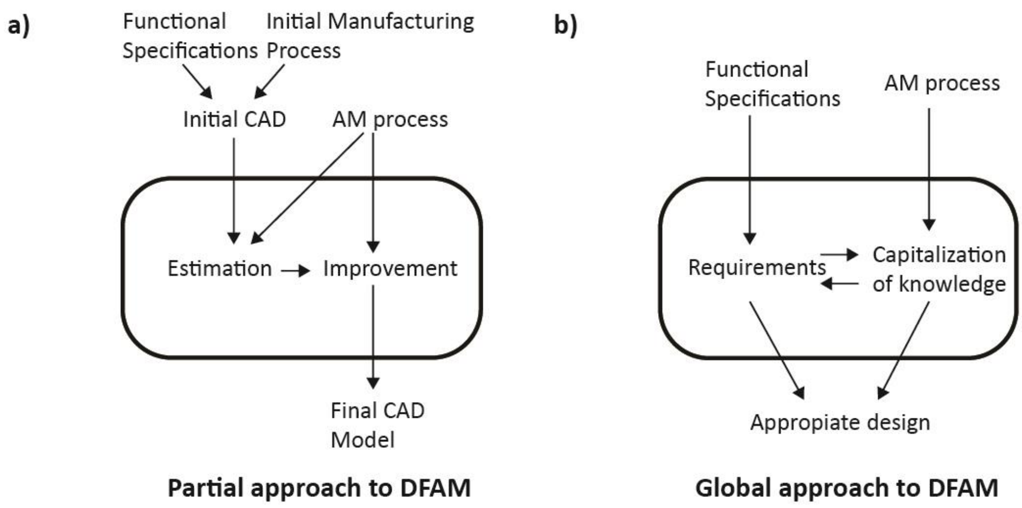


Figure 2.17. Partial and global approaches to DFAM. Adapted from Ponche et al. (2012)

Zooming out to a macroscopic level, DFAM groups have studied the development and performance of structural geometries. Regularly, manufacturing processes develop a set of best practices to make the fabrication of components more effective known as Design for Manufacturing (DFM). While these kind of rules are not needed in DFAM, geometrical considerations in AM are required in certain 3D printing processes (Adam & Zimmer, 2015; Suryakumar Simhambhatla & K.P. Karunakaran, 2015). Those considerations focus on the way standard structural elements and the selected material behave in the AM process. Standard elements are analysed in segments that correspond to basic geometries and the transitions between them. FDM has the most disturbances in the fabrication of structural elements. In order to design for FDM processes, part orientations, wall thicknesses, heights, and size of holes and slot tolerances should be revised. The fact that most of the current implementation of AM happens in new product development stages (NPD) shows that most of it uses designs that are thought to be manufactured traditionally in further stages. Transferring traditional designs to additive manufacturing can be considered a “substitution fallacy”(Stern, 2015).

With the transformation of design rules from regular DFM to DFAM, AM processes can exploit the flexibility afforded by computer aided design (CAD) to alter the digital model of the product as data or with data. New software applications are developed in order to control the complete material scope accessible to AM (Duro-Royo et al., 2015; Oxman, 2011). Further development of experimental 3D file formats and software that represent the totality of the material volume and not only the surface will allow the design of microstructures that make use of the available complexity to improve structural performance of printed structures (Gao et al., 2015).

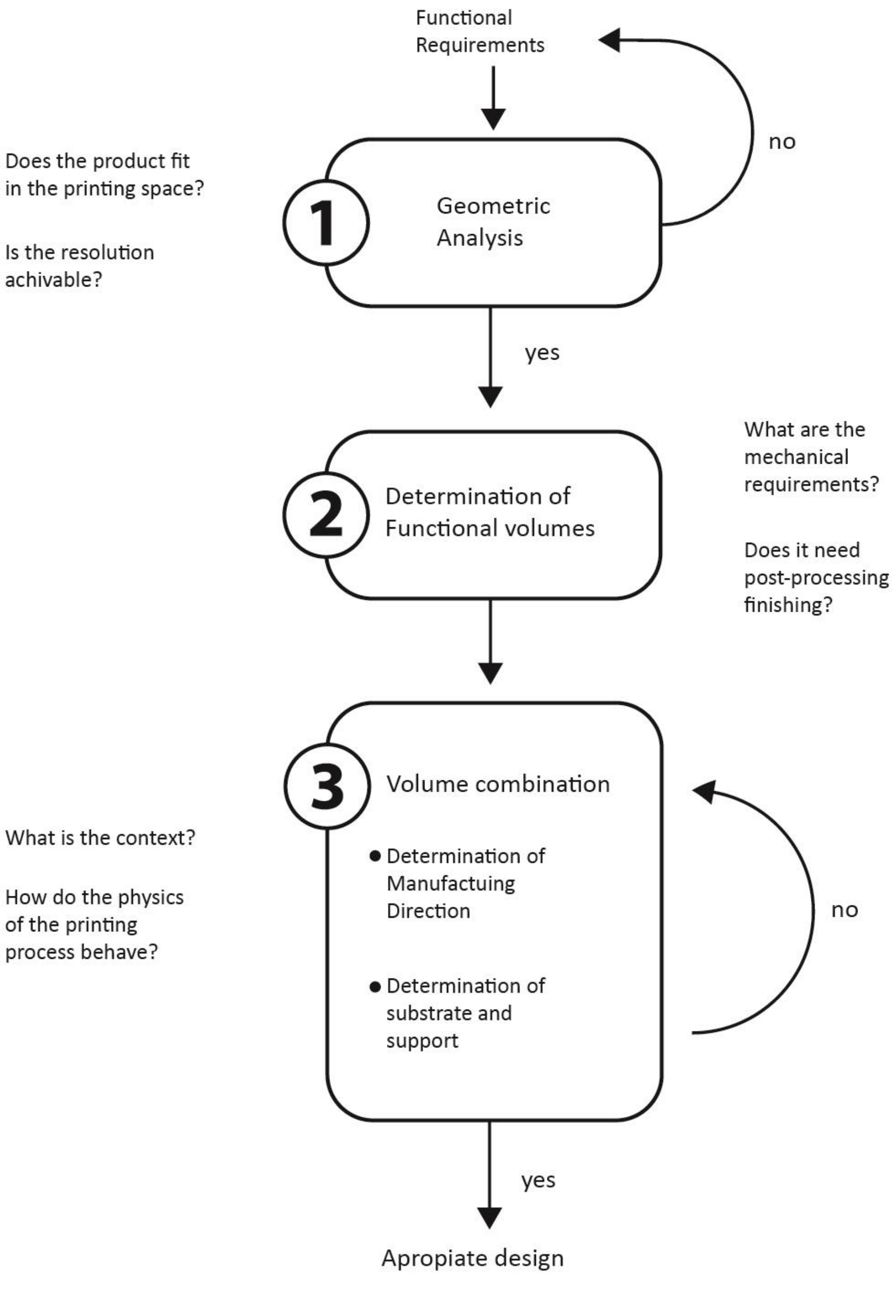


Figure 2.18. The global process of DFAM. Adapted form Ponche et al. (2012)

Merging design and manufacturing is considered a global approach to DFAM (Ponche et al., 2012)(Figure 2.17 and Figure 2.18). The purpose of a global approach is not to limit the result with an initial geometrical idea that will later be manufactured. Instead, the objective is to co-design with the technology. This approach requires the positioning of the functional requirements of the component into the printable volume of the used machine to let the CAD software connect the functional volumes with minimal dimensions usually using topographic optimization algorithms. The process ends with the evaluation of the geometric restrictions and the functional requirements of the final geometry. In a global approach to DFAM, entrepreneurs interact with the technology to generate different product architectures in a mode that is not considered in the study of new business opportunities due to the assumption of a partial approach to DFAM. NPD evolved with the Industrial Revolution separating the representation of the design artefact from the artefact itself (Hauck, Bergin, & Bernstein, 2017). The global approach of DFAM is among other factors such as CAD development and artificial intelligence (AI) that reconnect this intent with the manifestation of the artefact in the experimentation with AM.

DFAM connects the effectuation of market opportunities, product architecture and AM. In addition to the opportunities in business modelling, the alternatives in the implementation of a global approach of DFAM can operationalize the negotiation of product architectures in the effectuation process. Product functions could be freely included and renegotiated in the product architecture every time a new stakeholder is invited. Moreover, stakeholders and entrepreneurs can negotiate the artefact at the same time it is being built with the integration of CAD tools. With AM the entrepreneur has the ability to think beyond the restrictions posed by traditional manufacturing and propose strategies beyond the final product solution.

2.2 Models of Design and Entrepreneurial Ideation

Design is generally viewed as a decision-making process with the purpose of changing the surrounding conditions to a desired outcome (Simon, 1996). Empirical protocol studies of cognition in design have recognized two perspectives of the cognitive nature of designing that underlie the formerly reviewed theories: design as search, and design as exploration (Hay, Duffy, et al., 2017). The purpose of this section is to expose these views of design in order to illustrate the intersection of AM in entrepreneurial ideation.

2.2.1 Design as search.

Design as search views designers as information processing systems that interpret the problem through a sequence of cognitive operators (Simon, 1996). All the possible solutions from these transformations are already present inside possible combinations of the elements in the problem space. The effectiveness of design as search depends on the structuring of the available information inside this space. Diffuse and broad problem spaces correspond to illdefined problems, hence the design process makes use of structuring operations to transition between the different transformations of a possible solution. Design as search is the most prevalent description of design in Economics even though new economic perspectives propose alternatives. The practice of economics and finance in the twentieth century focused on a mathematical representation of economics that favours an *objective* perspective of markets (Mackenzie, 2006).The socio technological landscape of opportunity discovery is, from a design perspective, a problem space where entrepreneurs look for optimal decision-making (Simon, 1996). Thus, within Economics, design is a cognitive process used for the selection of solutions that negotiate between the external conditions and the desired state of the firm. Entrepreneurship as search entails entrepreneurs that design firms and submit them to the market mechanism. Thus, the discovery of markets engages in a correction cycle where entrepreneurs respond to the market feedback, adjust the algorithm, and re-submit the strategy to the market again (Ries, 2011).

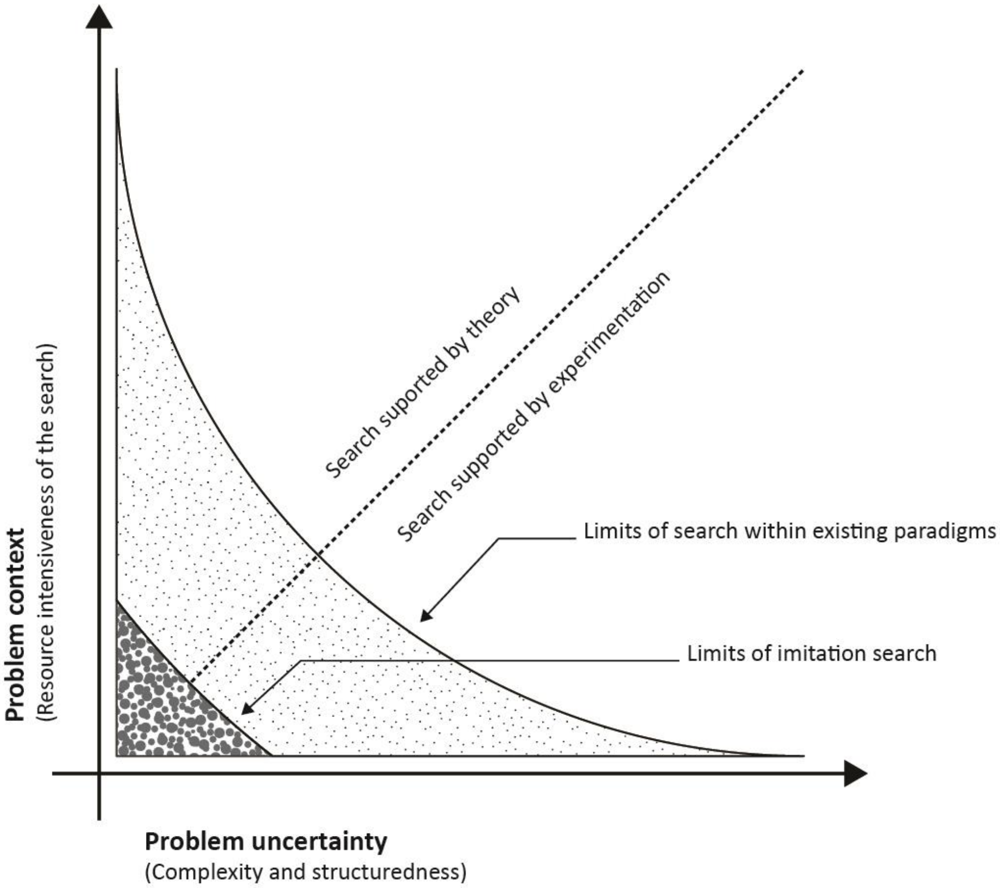


Figure 2.19. The problem space of entrepreneurship according to the resource intensiveness, and the uncertainty of the search. Adapted from Furr et al. (2016)

The entrepreneur is modelled as an information processing system that retrieves the cognitive operators from the long-term memory and transfers them to the working memory in order to manipulate the problem space. Figure 2.19 portrays the problems spaces as proposed by Furr et al. (2016). Inside tis representation, problem space is analysed in terms of contextual difficulty and the uncertainty of the complexity of its structure. The model suggests that different combinations of context and uncertainty require different search strategies and governance structures within the firm. Hence, the firm resembles a categorization of representations handled in the designer's mind. This portrays the ideation of strategies as a search through the symbolic representation and categorization of risk in the problem space (Garud et al., 2008; Jelinek et al., 2008; Porter, 1997).

When a problem space is properly structured, the symbolic representation of its elements is better manipulated into viable solutions in a linear way. One example of this interpretation in the implementation of Design thinking strategies for business modelling, is the utilization of human centred design techniques for the representation of customer personas in order to support the search of adequate solutions (Brown, 2008). Another example of search perspectives is enterprise ontology modelling which suggests that business failure is not related to uncertainty but to the lack of fidelity in the representations of the firm used in control processes. Engineering an enterprise ontology aims to give decision makers a reliable representation to ideate solutions that monitor possible misalignments between the business behaviour and the desired state (Dietz, 2011; Osterwalder, 2004; Uschold et al., 1998).

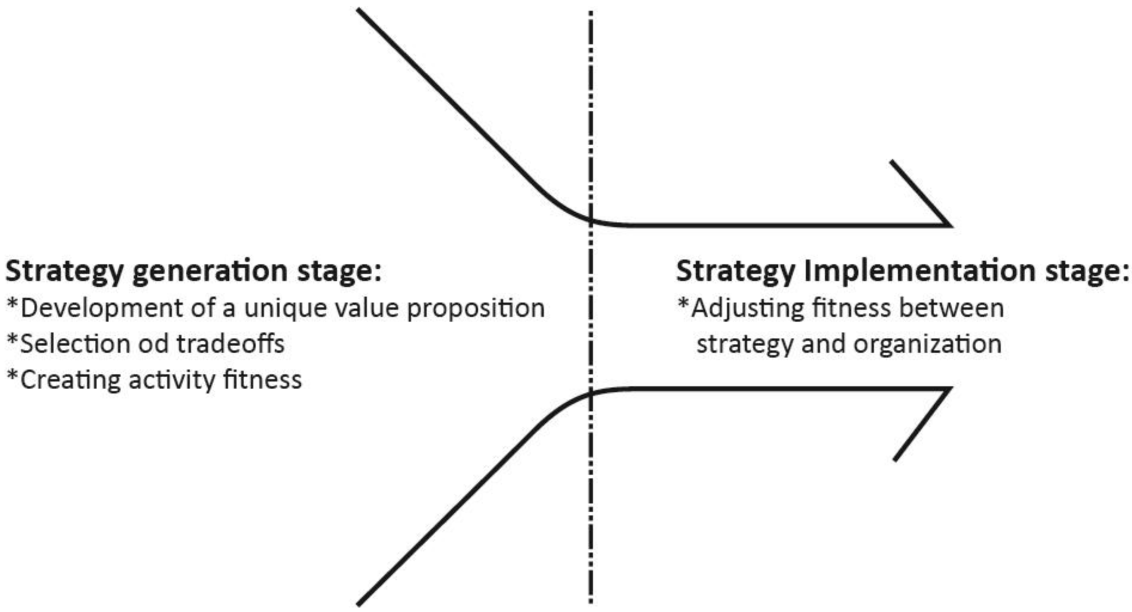


Figure 2.20. Design as search separates the implementation from the design process (Mintzberg, 1990).

The strategic design of firms in the discovery stream of entrepreneurship separates the design process in two stages of strategy ideation and strategy implementation (Mintzberg, 1990) (Figure 2.20). This perspective frames a design process that works top-down, from the strategist to the organization. The transaction is modelled "in essence", which means that its representation needs to be abstracted from the technological nuances of reality. The design of enterprises is the ideation of solutions for a black box model of enterprise through a white box representation of itself (M. S. Fox & Gruninger, 1998; Hoogervorst & Dietz, 2008). The literature that presents the benefits of AM works under this design assumptions.

2.2.2 Exploration design processes.

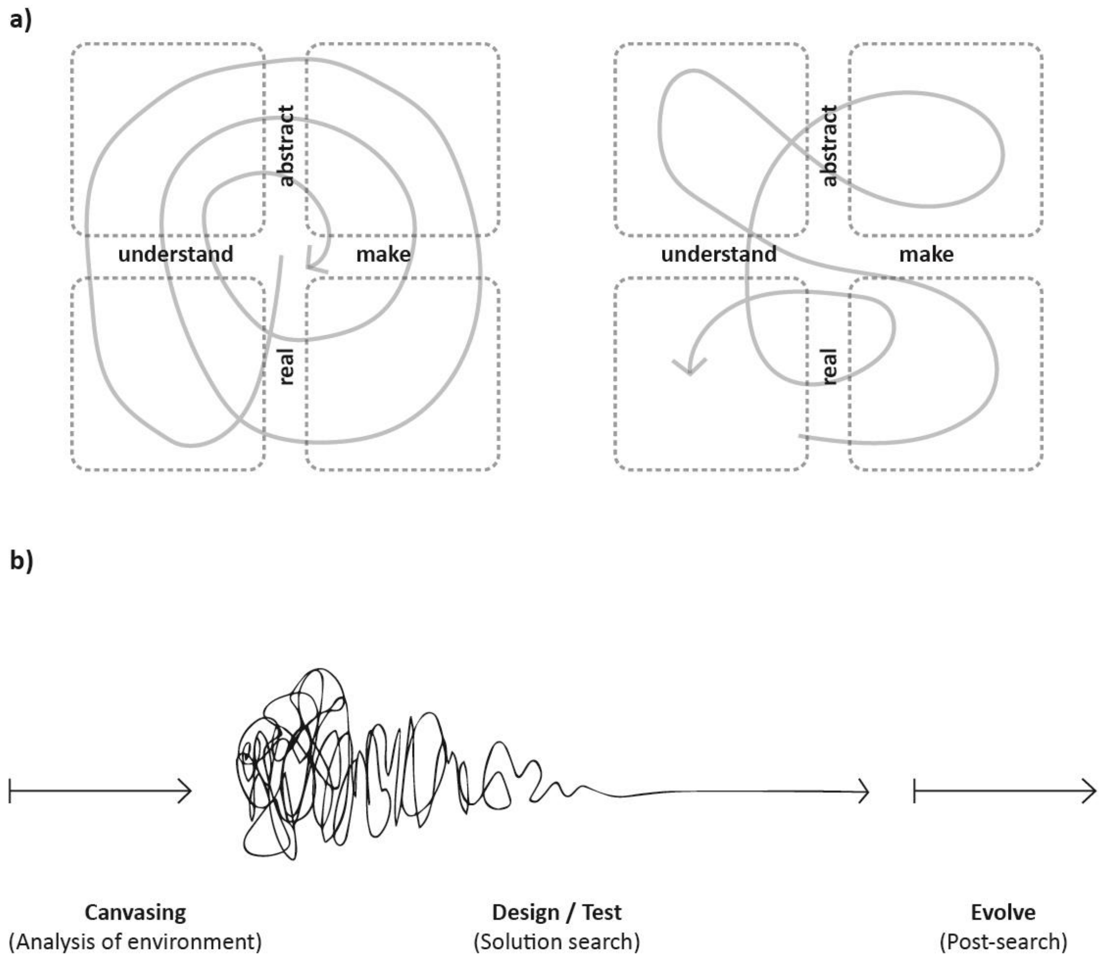


Figure 2.21. a) Design thinking is a non-linear process (Kumar, 2012). b) Interpretation of design thinking in business modelling (Osterwalder et al., 2015).

The alternative perspectives of creative entrepreneurship portray design cognition as exploration contrary to a linear search. Figure 2.21 shows the difference between this design process as visualized as exploration within the design scholars (Kumar, 2012), and the linear portrayal of design in strategy. This portait of design cognition is grounded on empirical studies where researchers studied the effects of design tools such as sketching and CAD (Bilda & Gero, 2007; Goldschmidt, 1994, 2014). These studies portray an iterative process from the acquisition and interpretation of information through the manipulation of solution manifestations. Design exploration divides the design space in two, a space for problem formulation, and a space for solution construction. Both spaces seem to co-evolve each representing a fitness function for the evolution of the other (Maher & Tang, 2003). In that way the interaction between them "may add new variables into both" changing the focus of the design process.

The visual manifestations of solutions in sketches or CAD, help the designer to alternate between modes of analogical thinking and the development of solution proposals (Hay, McTeague, et al., 2017). The first mode of analogical thinking, or "seeing as", interprets different properties of the means in the problem space by creating metaphorical alternatives of the manifested features. The second development mode, or "seeing that", solves the implicated design decisions that originated from the first step and builds a solution that transforms the first interpretation. Therefore, design goes through a cycle of perception, abduction of properties, and recreation through the visual manifestations where the nature of the manifested has influence over the development of both spaces.

Design as exploration explains the apparent "creative leap" of as a process where the individual finds a surprising or unexpected concept in the structuring of both spaces. By fixating on the surprising concept, the designer makes a bridge that facilitates the evolution process (Dorst & Cross, 2001). This surprise in the exploration of design has a clear relationship with the role of contingency in the creation entrepreneurship. The theories of entrepreneurial bricolage, the enactment of the organizing context and effectuation all reference a contingent solution based on the combination of the resources at hand. These processes evolve with the recombination of information from stakeholders creating novel interpretations of the same resources. In the same way, the effectual contract can be understood as an exploration process where two stakeholders are involved in the re-interpretation of their resources. The global approach of DFAM can also be considered an exploration process between the entrepreneur and the 3D printer.

The conception of design in Economics has a problem with the incorporation of interaction due to the prevalent naturalist view of markets. However, the difficulties of interpreting our interaction with firms and markets has also been acknowledged by some researchers as a pervasive problem for economics as a whole (Srnicek & Williams, 2015). According to these critiques, economic models are disconnected from everyday transactions and thus, inaccessible to interaction. Considering the pervasiveness of markets and their effects on everyday life, the economy needs to go through a process of mapping (Buck-Morss, 1995). Economic interactions could be eased through cognitive mapping of relations that clarify, from a human point of view, the entrepreneur's position, access and the effects of the market. Such mapping has the potential of making the interaction with resources more explicit and consequently, could help in the design of our actions and institutions (Jameson, 1988; Marsh, 2013).

Most of the examples of organizational design do not account for the embodiment of the organization and build accounts based on abstractions such as enterprise ontologies. An interactive market opportunity changes the discussion from whether or not to start a firm, to how to interact with the resources at hand in order to ideate the business opportunity (Sarasvathy, 2004). Effectual entrepreneurship is an alternative for designing organizations based on interaction. Yet, effectuation fails to describe the way the entrepreneur perceives the opportunities through the exploration of technology.

2.3 Entrepreneurial Ideation of Market Opportunities

Effectuation proposes to understand the firm as an instrument for the entrepreneur to achieve individual goals (Sarasvathy, 2004). Thus, effectual entrepreneurship changes the focus of design from the nature of the environment and the profile of the entrepreneur to the design of the firm and the market opportunity. The change of focus opens new avenues for the study of the interaction between entrepreneurs, contexts, artefacts. Who uses what kind of artefact? How is the firm organized without the actors? What are the effects or synergies that can be generated with other artefacts? These are different research questions that characterize firms as objects in specific contexts of use in the same way any other object of design.

Despite implying design as exploration in the enactment of the context, effectual entrepreneurship does not yet have the means to describe the ideation process beyond the influence of design as search. Sarasvathy (2004) attempts to define design using symbol manipulation:

> *“I am therefore going to try to explore at least two different perspectives from recent cognition research...The first draws upon the more familiar Symbolic Processing (SP) paradigm (also known as the problem-solving approach) of cognition. The second is more recent, and at the risk of wading too far into the unfamiliar, I will try to outline an approach based upon the work of George Lakoff (1987) and others using semantic categorization (SC) and conceptual metaphors.”* (Sarasvathy, 2004)

Therefore, it is necessary to articulate ideation in a way that recognises the exploration of artefacts, what Sarasvathy calls semantic categorization, such as the differences in manufacturing processes and the influence of the contexts of stakeholders.

2.3.1 Artefacts of design.

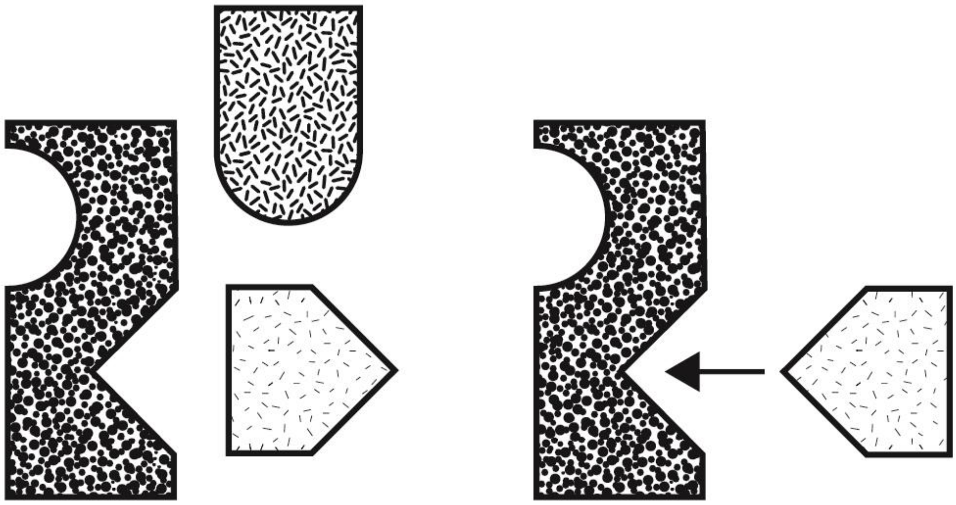


Figure 2.22. The environmental medium and substances bounded by surfaces (Krampen, 1989).

The exploration of market opportunities asks how firms are perceived and manifested as artefacts. Artefacts are always perceived at an ecological level (J. J. Gibson, 2014). Is it tall enough to fit? Is it heavy enough to lift? Is it close enough to reach? The physical world at the micro and macro levels is almost isotropic and regular (atoms and space). Yet, the ecological dimension where humans perform provides irregularities that organisms perceive and interpret to guide behaviour. Ecological irregularity happens in substances that are contained within a medium that can be traversed and transmit information (Figure 2.22). The surfaces of substances have layouts that present shape, scale, edges, and vertices. They form enclosures and objects. Through the complementarity of an artefact substance and an user organism both become one unit for the execution of the activity. Hence, forms in the medium become prosthetics for an organism that seeks the accomplishment of a goal directed behaviour (Martín Juez, 2002)

That which the environment and artefacts offers relative to the organism is called *affordance*. Affordances are not inherent qualities or specific features of objects or organisms but “invariant combinations of variables” that afford specific actions (J. J. Gibson, 2014). Affordances are relationships that depend on the artefact and the organism and consequently have no specific taxonomy. Object affordances make them ‘graspable’, ‘throwable’, ‘typable’, ‘readable’, or in the case of firm artefacts, ‘sellable’. Thus in the exploration of ideas, organisms do not perceive the representation of an object in their minds (as inferred buy the design as search), but the relevant affordances to exploration, that disclose what should be done with them (Chemero, 2003; Krampen, 1989). Affordances may be positive or negative, and make salient different levels of reasoning (Kannengiesser & Gero, 2011).

Different object layouts have an influence in the perceptual threshold of affordances (J. Lu & Cheng, 2013). Design manipulates perception by qualifying and manipulating the layout of the object. Humans qualify the grouping of affordances in guidelines and areas that are used to describe and prioritize functions and characteristics (Martín Juez, 2002). Designers make use of symbols or 'signifiers' to prioritize groups of features or areas for perception and guide use (Norman, 2011; You & Chen, 2007). Design operates at an ecological level where meaning is denoted by the reciprocity between objects and users. From this perspective, Creation entrepreneurship can be described as the design (through exploration) of an opportunity in an ecological level. Thus, design in entrepreneurship has an enormous opportunity in the analysis of firm perception within specific environments and their relationships with particular users and cultures (Esparza et al., 2017).

2.3.2 Entrepreneurial ideation as exploration of technology.

Design involves interaction with the artefact even before it is manifested in its final form in the exploration of ideas (Krippendorff, 2006). As designers of the business opportunity, entrepreneurs engage in the exploration of the product, firm and opportunity as artefacts. They enact these artefacts, and the technologies afforded to them, and ideate avenues for transaction making. Consequently, the technological affordances influence the spectrum of solutions available for the entrepreneur to decide. Hence, every time a design decision defines a feature in the final artefact, technical consequences will be fixed around its fabrication according to the available technology, as in the case of the mirroring process of product architecture (Ulrich, 2016). The early stakeholders assumed in this ideation process become the artefacts "bystanders" who carry the meaning of the artefact to language as in the model of the value network. In this sense, the exploration of early business opportunities ideates possible partnerships based on the exploration of the affordances of the entrepreneur's resources (Figure 2.23).

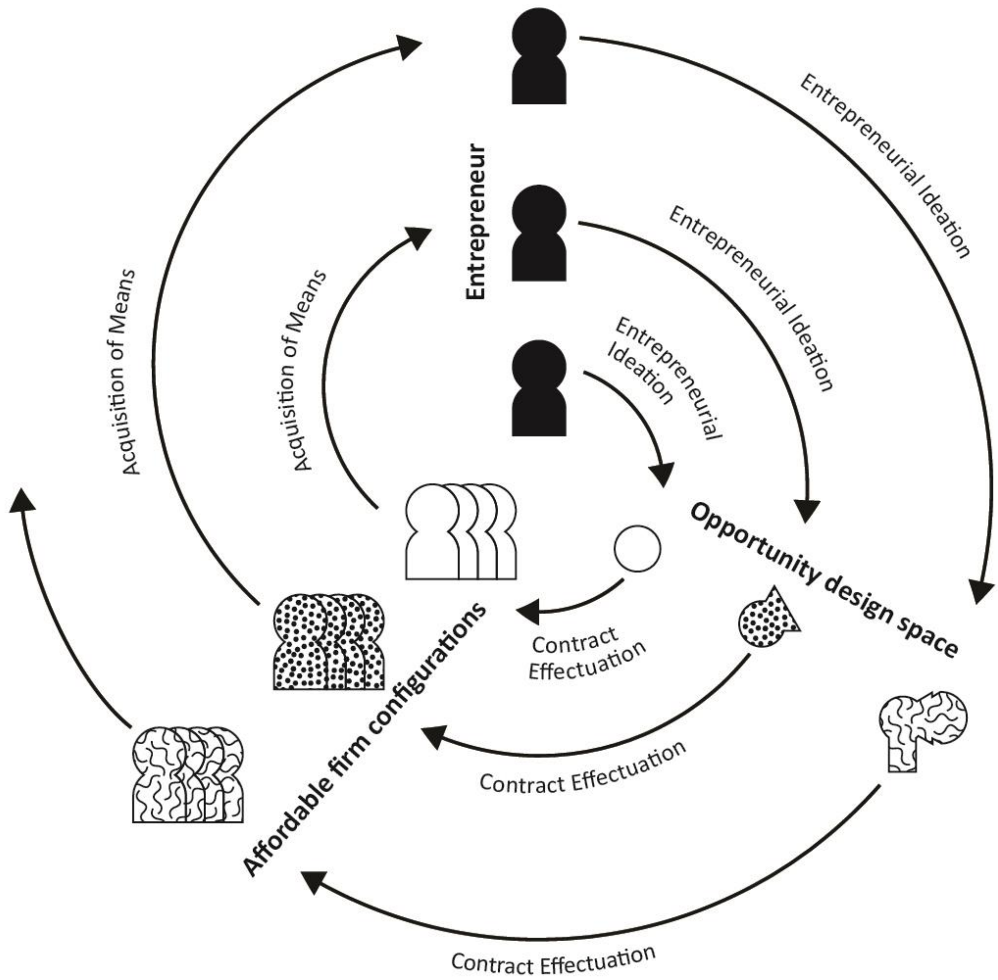


Figure 2.23. The accumulation of stakeholders influences the product and the subsequent inclusion of stakeholders in every cycle.

Through language, the fate of the artefact is decided in narratives, critiques, recommendations, blueprints, and in the case of entrepreneurship, in contracts (Krippendorff, 2006). The used language denotates the categories of artefacts and stakeholders generated in entrepreneurial ideation. The categories shaped from human experience are not logical or natural, technical or theoretical, as they only correspond to the perceptions and the discourses that assisted them. As one manifestation of such language, business strategy (especially in corporations) depends on the management of superordinate categories. The semantic manifestations of the firm such as logos, brands, advertisements, and even interior design manipulate these superordinate categories to convey messages for the end-users. In entrepreneurial ideation, new language categories ask users to stretch existing meanings that need the support of education campaigns to facilitate the recognition of new products and services (Hekkert et al., 2003). Contrarily, ideating with existing categories gives the designer access to existing vocabularies for meaning making.

2.3.3 Definition of research problem.

Changing the interpretation of entrepreneurial ideation from a search to an exploration process connects the role of the enactment of the technological means with the design of a business opportunity. In the ideation of a new market opportunity, the decisions around technology and the affordable product architecture have effects that have not been studied in entrepreneurship research and remain poorly understood. Partial approaches to the perception of the technology and its effects in the creation of organizations can be found in the concept of the value network. The model of the value network describes an environment of stakeholders within an industry, that is articulated by the way performance is understood and measured through a product architecture. Yet such perspectives do not describe the cycle of perception and ideation thoroughly. Therefore, the articulation of the theories presented in this literature review aims towards filling a gap in the theses that describe the way technology affordances modify entrepreneurial ideas which is particularly important in the implementation of AM.

This proposal analyses the role of the enactment of AM means in business making. The research problem space of this project lies within exploration of affordances in AM technologies. Consequently, the research project proposes that the study of the affordances of complexity freedom and its effects on the exploration of new business opportunities.

2.4 Chapter Summary

The literature review portrayed a comparison of parallel theories of market opportunity formation in the study of creative entrepreneurship and the mirroring process of product architecture. Creation entrepreneurship is a stream of research that is characterized by describing the origin of markets as a process where entrepreneurs enact the resources, they have at hand to create market opportunities. Entrepreneurial effectuation stands out from other approaches of creative entrepreneurship and suggests that the creation of markets originates in the co-creation of the opportunity through the negotiation of contracts. This perspective of market creation resonates in the models of product architecture that describe the creation of industries. The review describes these concepts, and shows how the configuration of product architecture has effects over the firm's formation, its performance, and structure. These theories propose that industries are originated in *ferment* periods where many solutions to perceived needs are created with different product architectures. The effectiveness of the best design and the network effects of the actors make a dominant effect that defines the architecture as an industry standard. The *solidification* of the design extends to the manufacturing organization and later to the industry itself. Thence, this review proposes that the models of the creation of organizations in the fields of entrepreneurship and technology management, are different perspectives of the same phenomenon.

The review continues to contextualize the frameworks used to describe the implementation of entrepreneurship and product architecture with AM. Contrary to traditional manufacturing, AM has complexity freedom which enables the incorporation of more functional volumes without increasing the fabrication cost. Under the lens of effectuation, the literature review suggests that AM has the potential to transform the product architecture to incorporate more stakeholders in the process of opportunity creation. Theories of entrepreneurship and product architecture fail to articulate this potential because they perceive the product design process as a search process.

This chapter contrasts models of design as search and design as exploration that underlie the bodies of entrepreneurship and technology management, to articulate the possible effects of AM in entrepreneurial ideation. Contrary to design as search, design as exploration recognizes that ideation is the result of the interaction between a problem and a solution space. The theories of interaction highlight the need to recognize the design process as an ongoing one where the exploration of market opportunities happens through interaction with the means of the designer, or in the case of venture creation, the entrepreneur. The literature review points out the need to study the firm as an artefact, and the interplay between the artefact and the designer. Finally, it defines the gap in the literature that appears when the fields of entrepreneurship, technology management, AM, and design overlap. It suggests that the study of the interaction with AM needs insights of how business ventures are ideated under the influence of new manufacturing technology.

3 Methodological Framework

3.1 Nature of Affordances in Market Opportunities

Market opportunity creation is nested in the realm of ideas. A market opportunity in the study of entrepreneurship has been defined as *"situations in which new goods, services, raw materials, markets, and organizing methods can be introduced through the formation of new means, ends or means-ends relationships" (Eckhardt & Shane, 2003).* These entrepreneurial situations are manifested through the ideation of a possible future that must be enacted in order to make the opportunity true. Reviewing the concepts of creative entrepreneurship, an entrepreneurial opportunity is the result of the combination of individual ideas and actions that develop through an iterative process (Dimov, 2007). From an exploration perspective, the effectuation of markets (Sarasvathy & Dew, 2005) is a continuous transformation of ideas through the exploration of the means found in the entrepreneur's context. Consequently, entrepreneurial ideation cannot be studied in isolation but as afforded relationships that turn into opportunities through the exploration (Figure 3.1).

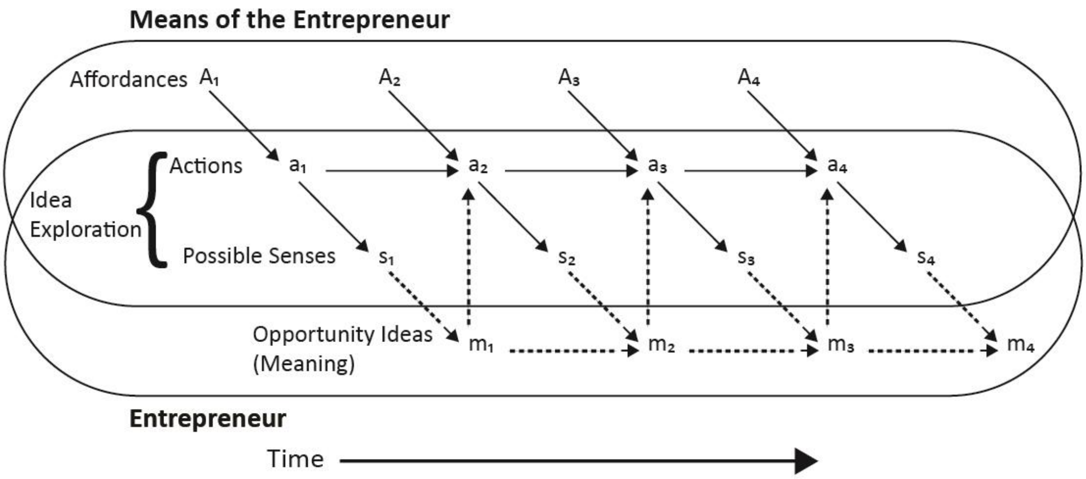


Figure 3.1. Affordances in the effectuation of markets. Adapted from Krippendorff (2006)

The methods used until now to study firm creation and the benefits of *Additive Manufacturing* (AM) consider just one of the extreme poles of the interaction. Naturalist perspectives in discovery entrepreneurship and technology management use methods designed to find causality in the contextual conditions of the business venture. On the contrary, creation entrepreneurship studies tend to have a constructivist view which tends to analyse the opportunity from a behavioural perspective without attention to the environmental conditions of the ideation environment. Both interpretations are unable to account for the nature of affordances by studying just one pole of the affordance spectrum. Thus, the difficulty faced in validating the study of entrepreneurial ideation lies in the opposing limitations that both naturalist and social constructivist approaches have correspondingly.

The study of *entrepreneurial ideation* in this thesis requires a shift that focuses on the relationships generated from affordances in technology that are involved in entrepreneurial ideation. The following sections address three main concerns: an epistemological perspective that recognizes the nature of affordances, a methodology suited for the inductive nature of the project, and the methods chosen to operationalize *complexity freedom* and document its affordances.

3.2 An Ontology and Epistemology for Affordances

The contingent nature of ideation processes complicates the definition of affordances and their agency in the ideation phenomenon (M. L. Anderson et al., 2012; Chemero, 2000). Yet, the apparent subjectivity of these contingencies does not correspond to the patterns shown in the evidence of dominant designs and mirrored structures. Interactionism proposes that agents and contexts are not radically separated but dialectically interrelated (Agre, 1997). Interactionism highlights the contingency of the relationships generated between agents and context. Agential realism is an interactionist ontological stance that reconciles the contradictions of naturalism and structuralism. Accordingly it was chosen to represent the entangled nature of affordances as relationships that otherwise would be adjudicated causally to the resources of the entrepreneur or to the entrepreneur herself. Agential realism brings an alternative to critics of existing theory that disqualify each other based on naturalist or constructivist approaches (Arend et al., 2015).

In agential realism, the objects of study are not agents or objects but their agencies as inseparable actors in entangled phenomena (Barad, 2003). Agential realism argues that agents and relations cannot pre-exist each other, as they cannot be determinate outside the observed phenomenon. Agents are entangled in the enactment of the phenomenon. In agential realism, these indeterminate phenomena is made determinate through the material enactment of discursive practices. These practices set partial boundaries to the phenomenon to the extent and alignment that both matter and discourse allow. These practices enact determinate differences within the phenomenon by highlighting certain agencies over others. Through material discursive practices, causal relationships and meanings arise making agencies intelligible to the actors involved (Barad, 2007). One instance of these enactments is the entrepreneurial exploration of affordances.

Agential realism brings objectivity to the account of relationships between entrepreneurs and the surrounding context. Barad (2007) indicates that agents with the ability to respond to the intelligibility of discursive practices generate meaning. Scientific enquiry can be considered part of this intelligible intra-action of the phenomenon when methods intervene. Instruments, theories, models are all apparatuses that embody material-discursive practices. Accordingly, they actively differentiate causal relationships that correspond to the discourses they use to highlight correspondences in the actors that intra-act the phenomenon. This cut of agencies does not solve the entangled nature of the phenomenon, but only separates them momentarily for examination. Therefore, objectivity in agential realism lies in the control of this agential cut which guarantees the repeatability of the experiment and the generalisability of the insight. Agential realism provides an epistemological frame to design a study of affordances that differentiates within the entanglement of technological affordances and entrepreneurial exploration.

3.3 Methodology Development

This project consisted of the development of studies (or a *research apparatus* from an agential realist point of view) that selectively enacts an agential cut of the affordances between AM and the entrepreneur. This project has adopted an inductive approach to define the possible configurations of this research apparatus. Inductive analyses are characterised by *"approaches that primarily use detailed readings of raw data to derive concepts, themes or a model through the interpretations made from the raw data by an evaluator or researcher" (D. R. Thomas, 2006)*. Accordingly, the objective of this approach is to condense data, establish clear links that enable tracing decisions back in order to preserve validity, and develop a model of afforded relationships in entrepreneurial ideation, acquired from complexity freedom.

The inductive methodological structure adopted a partial grounded theory approach for the development of the research apparatus based in design thinking. The grounded theory approach is used to refine the design of the agential cut and the choice of the methods that will intervene the entrepreneurial ideation. This thesis complemented this approach with design as inductive sensemaking for the selection of methods (Kolko, 2009; Liedtka, 2000). For Klein et al. sensemaking is a form of making meaning out of data that works with cycles of framing and re-framing information (Klein et al., 2006). Design research uses these framing cycles to form insights from raw qualitative data (Kolko, 2011). The implementation of design processes in research can surface new kinds of knowledge that are not available without it

(Fallman, 2007). This design-assisted grounded research approach refines the theoretical framework in cycles from data to prototype to method to theory in every iteration.

3.4 Methods

This inductive methodological stance looks for internal validity through experimental methods. Experimental methods for the study of entrepreneurship are seldom used (Crook et al., 2010). The application of experimental methods has been also proposed as an alternative to existing methods based on hindsight accounts (Davidsson, 2007, 2016; Sarasvathy, 2008). These methods have been used to create a coherent environment with enough internal validity in different studies of creative cognition (Finke, 1996; Fu et al., 2013). Experimental methods create the opportunity to examine the success of creative processes that depends on complex systemic influences that are difficult to frame (Csikszentmihalyi, 2014). In the same manner, experimental methods create an environment that favours the simulation of closed entrepreneurship processes that otherwise occur in very long time lapses (Cassar & Craig, 2009). Experimental methods avoid the collection of information altered by hindsight bias. This study of affordances in entrepreneurial ideation focuses on the exploration of opportunity ideas and the corresponding features in technology that influence their creation in the moment they are created.

The choice of experimental methods also facilitates the examination of tools that have already been developed for the study of creative cognition in psychology and design. Methods that analyse design as exploration have been developed from think aloud protocols of design tasks (Dorst & Cross, 2001). The study of design as exploration has further developed methods that study the co-evolution of design manifestations and design concepts (Belmonte et al., 2014; Bilda et al., 2006; Bilda & Gero, 2005, 2007). This study of entrepreneurial ideation used a similar structure where participants are presented to a set of means that are used to design a creative output.

The indeterminate nature of the affordances and the grounded approach of the study was analysed with a mixed methods approach. The purpose of a mixed analysis is to attempt to create a complete image of the complexity that surrounds entrepreneurial ideation. The articulation between qualitative and quantitative methods in the study of entrepreneurial ideation can complement independent views of the method (Denscombe, 2008). This study implements a complete analysis embedding qualitative data in quanitative frameworks (Kara, 2015). With this quantitisation of themes this project also seeks to demonstrate that the phenomenon of interaction is more complex and that further analysis of the phenomenon can be approached in both ways.

3.4.1 Methods summary.

The chosen methods synthesise the strategies presented above in the context of entrepreneurial ideation with complexity freedom. The structure of the methods seeks to expose the qualitative and quantitative properties of the affordances that play in entrepreneurial ideation. The methods focus on the afforded complexity that complexity freedom provides to new market opportunities. Complexity is a property of novel opportunities that have products with interdependent components different from existing bids in the market (Colfer & Baldwin, 2016; Jesus Felipe et al., 2012; Mike Hobday, 1998). Products that are innovative are also more likely to have complex organizations that preserve highly technical and valuable transactions inside the structure of the firm (Hart, 1988). This study analyses entrepreneurial ideation through the comparison of opportunity idea and product complexities when afforded through AM. The developed methods expose these relationships in entrepreneurial ideation through the following research questions:

Q1. How does complexity freedom impact early entrepreneurial ideation?

Q1a. How does complexity freedom affect product architecture in entrepreneurial ideation?

Q1b. How does complexity freedom affect the structures of ideated firms?

In engineering design, complexity is defined as the measure of uncertainty in achieving the artefacts functional requirements (S. C.-Y. Lu & Suh, 2009). Integral product architectures present higher degrees of complexity than modular architectures. Analyses of complexity are present in the study of product architecture and the comparison between different architectures and their organizations (Baldwin & Clark, 2000; Sanchez & Mahoney, 1996; Ulrich, 1995). Yet, the analysis of architectures is restricted to the functional structure of the product and does not recognize afforded meanings of stakeholders. However, the analysis of value networks that uses diagrams of nested hierarchies provides an alternative view of the structure of a product that shows the formation of semantic categories of components and the stakeholders that recognize them (C. Christensen, 2013; C. M. Christensen & Rosenbloom, 1995). The following methods aim to expose the affordances of complexity freedom in ideation by analysing the structural complexity of the product itself and the first instantiation of the value network. The methods limit the analysis to the level of market interaction that corresponds to the entrepreneur.

The cycles that refined the manifestation of complexity freedom and ideation according to the grounded theory approach, began results began exploring the frameworks of DFAM listed in the literature review. Next, Study 1 refined the simulation of the design of a product with AM based on methods used for the study of design manifestations. The final method was implemented with 24 participants. The results were used to isolate the complexity variable in a way that could be implemented with a bigger sample in Study 2. A summary of the evolution of the methods is presented next. Study 1 and Study 2 are expanded in chapters 4 and 5 respectively.

Implementation of DFAM frameworks.

The implementation of the frameworks of Design For Additive Manufacturing (DFAM) was used to contrast the different approaches of the field and contribute to the grounded development cycle. This stage identified factors that affect the implementation of the final methods. Five implementation areas were selected to be explored:

- Material properties, complexity and customization
- Generative algorithms
- Topographic optimization
- A global approach for DFAM
- Speculative design with AM

Each area was explored through the design and fabrication of an object presented in the appendix: **AM exploration exercises**. The implementation of these projects disclosed that complexity freedom in customization and manufacturing flexibility is not only manifested explicitly by the printer itself but is interfaces by a system of tools and the design capabilities in the entrepreneur/designer. The utilization of 3D modelling, Finite Element Analysis (FEA), and Finite Element Synthesis (FES) environments assisted in the manipulation of material and geometrical levels of design. The same tools facilitated the inclusion of more functional requirements at different levels. Likewise, at a process level the global design approach (Ponche et al., 2012), facilitated the incorporation of the machine in the design process as suggested. The exercises also show that implementation requires a certain level of experience in NPD and AM in order to achieve successful results. This presents a challenge for the research project because the proposed benefits of AM in new business creation are not exclusive to expert designers. The process extracted three core insights for the development of the methods:

1. Elimination of CAD interfaces: The exercises showed that some of the techniques that are used to add complexity to the version of the product that will be manufactured require specialized expertise modelling and pre-processing software and thus, must be reduced as possible.

2. Clear visualization of product architecture: Exercises with generative design showed that through AM the product architecture merges the perception of components that correspond to functional volumes. The design of the studies focused on making product architecture more explicit to avoid false perceptions.

3. Facilitation of design processes: Incremental complexity can push the designer to spend more time in the development of the technical aspects of the geometry instead of addressing strategic concerns. Hence, it was decided that final studies should eliminate technical aspects of product design that are not related to product architecture.

Study 1: Study of product structures influenced by complexity freedom.

A simulation exercise of entrepreneurial ideation was implemented using a building kit in an entrepreneurship context (Figure 3.2). The structure of the activity was designed based on studies of the effects of design manifestations in design (Belmonte et al., 2014; Bilda et al., 2006). The objective of this study was to expose the effects of complexity freedom in the resulting object of entrepreneurial ideation. The study implemented a set composed by a brief, and a building set that reduced the use of intermediary tools between the user and the built product. The brief described a trend that they should take advantage from with the introduction of a new product in partnership with other entrepreneurs. Participants were split between two different groups, the control group that interacted with the building set under traditional manufacturing conditions, and the control group that interacted with the set under AM conditions. Within each group, participants assembled teams of 3-5 participants. The brief gave each participant a non-shareable budget they could use to contribute to the business venture.

Figure 3.2. Implementation of design task.

The design of the building kit was composed of two different building blocks and a cost management spreadsheet. The building blocks belonged to two different categories: material, and complexity blocks. For the control group, material blocks increase in cost proportionally while access to higher complexity blocks increases according to the number of axes it unlocks for the assembly of the material blocks. For the experimental group, the cost of material blocks increases proportionally but the cost of complexity blocks is null. Both sets of costs were based on real comparisons of high-pressure metal die casting and additive manufacturing processes (Atzeni & Salmi, 2012).

The results were analysed qualitatively and quantitatively. A typology of the designs was drawn from the observed prototypes according to their general categories and their level of interactivity. The complexity of the prototypes was evaluated by measuring the number of elements and the maximum level of complexity blocks used. Descriptive statistics and a simple T test were used to analyse the quantitative data. Main insights of this study pointed out to the further isolation of complexity for the next study. The method and results are described thoroughly in chapter 4.

Study 2: Study of the effects of complexity in semantic entailments of entrepreneurial ideation.

Study 2 mapped the entrepreneurial ideation task to a mental imagery exercise (Finke, 1996). A mental imagery exercise restricts the interaction with the ideation stimuli to the mental exploration of visual inputs and their interpretation. The study used a generative algorithm to generate random configurations of 3D modelled volumes for this purpose (Figure 3.3). Such volumes were classified according to the number of components and symmetry as indexes of their complexity. The figures were presented to participants as means for entrepreneurial ideation. Participants were asked to imagine a product to start a company with. Furthermore, they were asked to complete 13 statements that concern firm creation such as: product functions, customer segments, and possible partnerships. The exercise was distributed through an online platform gathering 308 valid responses.

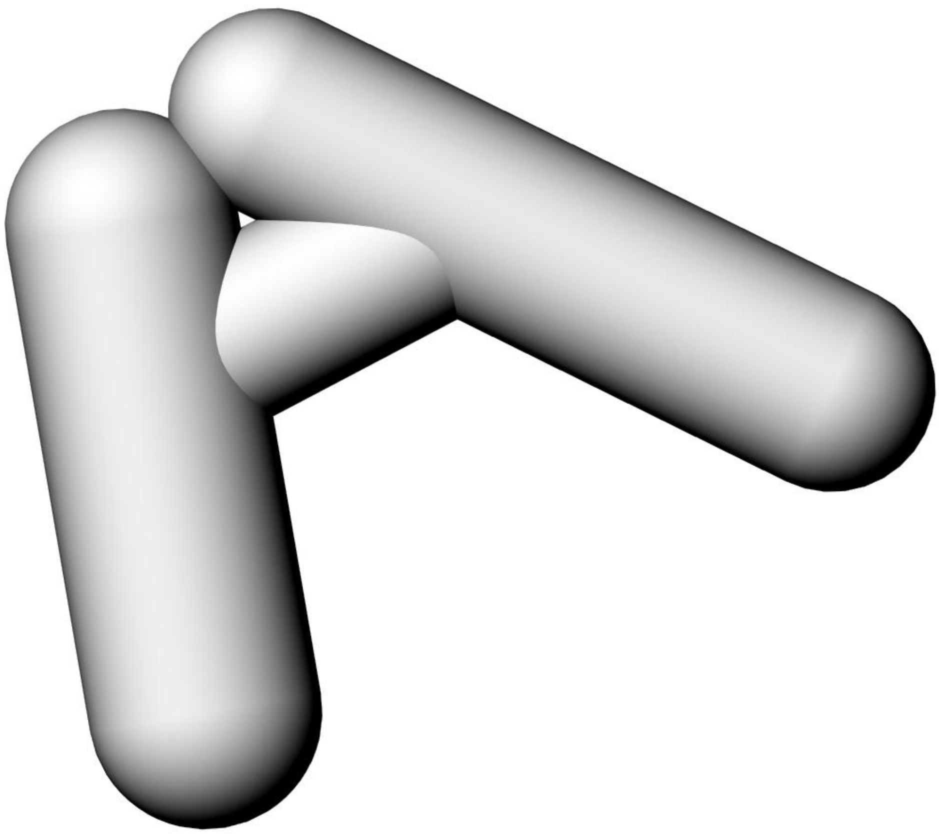


Figure 3.3. Example of images chosen for the exploration of mental imagery.

The collected responses were processed using a Natural Language Processing Toolkit (NLTK Project, 2017). Next, they were manually classified into themes using the most specific instantiations of object and identity categories mentioned by the participants. The complete processed text was used to create a network based on the semantic relationships amongst them. The complexity of each answer was analysed based on the available connections between the mentioned words in each answer. The analysis was also run for each answer, group of answers from the same participant, group of answers corresponding to the same item and the same image, the same image, and the complete universe of answers. Statistical analyses were used to look for differences between samples that used different levels of complexity. The complete details of the method and results are described in chapter 5.

3.5 Chapter Summary

This chapter presented the methodological framework and rationale that were used to design this study. It described the nature of entrepreneurial ideation of market opportunities. It exposed the conflicts that traditional research perspectives present for the study of entrepreneurial ideation. It continued to present three adopted strategies for the development of the methodological stance. It described an agential realist account of affordances and its relationship with the methods used for the study of entrepreneurial ideation. It continued by describing a general inductive approach to narrow down method design and a partial grounded research approach in the use of design as a way of scientific knowledge development. Next it presented the case for experimental approaches for the study of entrepreneurial phenomena and the use of mixed methods for complementing the analysis of data.

The chapter provides a description of the selected research methods. It presents a summary of the practice of reviewed DFAM frameworks. Secondly, it introduces Study 1 focused on the operationalization of complexity freedom through a building set that represent the manufacturing means. Results were categorized in object typologies and later compared according to their complexity. Finally, it introduces Study 2 which mapped entrepreneurial ideation to a mental imagery exercise. This study focused on the effects of varying degrees of complexity over descriptions of market opportunities. The study used a generative algorithm to produce random product architectures of varying complexity that could be used as means for entrepreneurial ideation. The images were introduced to participants through an online survey. Results were classified manually and analysed statistically in order to compare the effects of complexity.

4 Study 1: Product Design with AM

A design task in an entrepreneurship scenario is used to study the emergence of *entrepreneurial ideation* when interacting with complexity freedom. A design exercise draws boundaries that expose the external influences of entrepreneurial ideation. It also enables the design of an activity that isolates complexity freedom from *Additive Manufacturing* (AM) tools. The task used different versions of simplified AM interfaces until the representation of such technological interfaces facilitated the representation of the variables, the environment, and the results of entrepreneurial ideation with detail. The hypotheses of the study are described as follows:

H1. Complexity freedom will facilitate the ideation of complex product architectures.

H2. Complexity freedom will facilitate the development of interactive affordances in the results of entrepreneurial ideation.

The experiment focuses on the business opportunity as the object of entrepreneurial ideation. AS reviewed above, the business opportunity has been defined as the articulation of an idea with the purpose of its introduction to the market (Dimov, 2007). The main objective of the design task was to portray the exploration of business ideas through the simulation of complexity freedom. Complexity is the uncertainty in achieving an artefact's functional requirements. New products are introduced through integral architectures where components have high interdependencies between them (P. Anderson & Tushman, 1990; Ulrich, 1995). Interdependencies of integral architectures increase the product's inborn complexity while the development of the fabrication requirements increases its acquired complexity (S. C.-Y. Lu & Suh, 2009). AM technologies deposit only necessary material regardless the shape of the fabricated product. Thus, production with AM has the same cost for any geometry as long as it requires the same amount of material (D. I. Gibson et al., 2010a). The lack of acquired complexity in AM is called *complexity freedom*. The exercise controlled the conditions that produce complexity freedom as the independent variable of the study.

The study measured the effects of complexity freedom in the product architecture and the suggested affordances of the product. The study documented the results of ideation using the number of elements that compose the system and the interconnections amongst them. Parallel, a qualitative analysis looked for interactivity as a measure of the involvement of different levels of cognition in the suggested affordances described by each participant. Kannengiesser & Gero (2011) propose a taxonomy of affordances in design that classifies their interactivity according to the involvement of three levels of cognition. *Reflexive* interaction works as a direct response to stimuli, a component or feature with a direct mapping of actions. *Reactive* interaction opens a linear dimension for the user. Reactive affordances let the user select from a range of values embedded in the activity. *Reflective* interaction involves changes in the context and user goals that let the user explore possible uses of the artefact. The higher degree of cognitive involvement is measured as a proxy of inborn functional complexity.

4.1 Task Brief

The use of fictional scenarios for design research is common in studies of design processes (Dorst & Cross, 2001; Hay, McTeague, et al., 2017; Yang, 2009). The task incorporated methods used for the study of creativity to portray an entrepreneurial scenario in practice (Dimov, 2007). The adaptation of the structure of these methods was developed in stages in order to preserve the validity of the manifestations of complexity freedom and the entrepreneurial environment.

Initial iterations of the task were open, inviting teams of entrepreneurs to brainstorm ideas freely after receiving an introduction to AM technologies. Open ideation should leverage the entrepreneurs background for opportunity creation (Sarasvathy, 2008). Nevertheless, the implementation failed to guide entrepreneurial ideas to AM execution. There was an uneven understanding of manufacturing conditions that clearly biased the ideation process. Additionally, the scope of the ideas was extremely variable with some entrepreneurs proposing whole systems with several products that required several design processes.

The final task was structured through the creation of a brief and a building kit that simulated the manufacturing process and homogenized the means for all participants. It gave a non-sharable budget for each entrepreneur and specific conditions to use it according to traditional and AM processes. The description of the budget included an imaginary currency that would avoid comparisons with the purchasing power of each of the entrepreneurs. The brief also provided the instructions of the task and a description of manufacturing kit. Instructions asked entrepreneurs to form groups of 3 to 5 people. The teams were assigned randomly one of the two versions of the brief. Teams that received the first version constituted the control group and contained kits that represented traditional manufacturing. Teams that received the second version were included in the experimental group and received kits that represented AM.

The brief depicted the following scenario:

The ping-pong ball challenge

It is 2020 and a new game has caught the minds and hearts of our generation for the last 3 years! What started as a YouTube video in 2017 is now becoming an institutionalized sport all over the world. Every day new players gather in clubs to compete making semi-professional leagues.

The number of people who play this game is increasing. It is calculated that 30% of all teenagers from 13-17 years old play this game at least two times a month.

This increase in the playing population has also opened a blue ocean full of market opportunities!

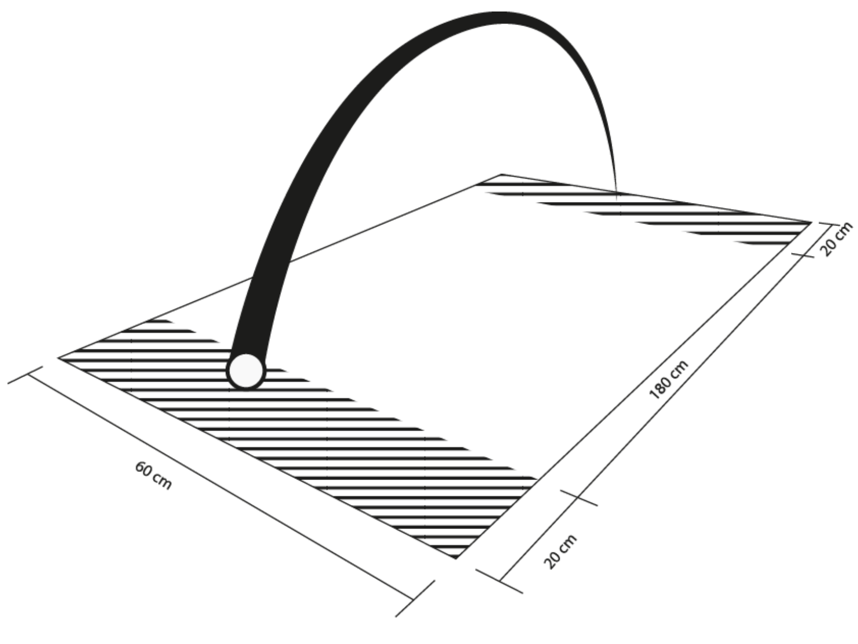
What is the game about?

People have lost their minds with this simple game.

The objective is to move a ping-pong ball from one end to another without touching the board between the ends!!! Players agree on the distance to be covered, but 180 cm. is the most common board size.

The only rules are to keep the ball inside the 60 x 20 cm areas at start and end of the challenge. You should not let the ball touch the board between the ends. The faster ball wins!

People have created many different devices to compete in this challenge. They look for something reliable and affordable that they can tune up for different contests.



Your budget is:

₸1,250,000.00

Your conditions are:

Each of you produces one component

You can't share your budget

You can't share your unlocked moulds (complexity levels)

Groups had 60 minutes to build a solution based in the combination of their individual components. After this period, the teams filled a spreadsheet that described the product and the involved costs for a hypothetical production run. Thereafter, the entrepreneurs tried their designs in a "contest" for entertainment purposes.

4.2 Development of the Building Kit

Examples of design kits that enable the study of creative processes in NPD exist in design literature. It is proposed that the material provided to the participants affects the possible results of the creative activity by creating constraints for the inclusion/exclusion of particular decisions in design (Karana et al., 2008). Since AM is mediated through software environments, the development of the kit had the purpose of reducing the need for software operation expertise while operationalizing the features that concern to functional allocation.

Five versions of kits were prototyped: sketch, designer assisted, software, diagram, and building set. Sketches have been studied as tools that enable design thinking (Bilda et al., 2006; Bilda & Gero, 2005, 2007). The experiment was first proposed with a kit where entrepreneurs sketched their ideas and annotated the different components that composed the proposed product. In practice, sketching became uncomfortable for participants who did not feel that their representations were accurate. A different approach used a designer as an assistant for the creation of such sketches. Yet, entrepreneurs spent more time adjusting sketches to their mental representations instead of idea generation. The use of software for design has also been tested using students from design backgrounds (Belmonte et al., 2014). Hobbyist oriented modelling software such as Autodesk Meshmixer (Autodesk, 2017) and Tinkercad (Autodesk, 2016) were also used to prototype the exercise. Nevertheless, entrepreneurs that had not used such interfaces found similar difficulties when using a 3D modelling environment. In these three versions of the kit, the manifestation of complexity freedom became more difficult when entrepreneurs had to allocate functions to components with unclear limits amongst them. Drawn diagrams proved to be more effective with entrepreneurs when delimiting the extent and size of a component but struggled with the inclusion of nested subsystems. The relationship between the overall functions of distinct components became unclear and functions that were contradictory were not explicit to the participants (like containing liquid vs pouring). The final version of the kit materialized the diagrams in items and connections which made material and complexity quantification easier to understand. At the same time, the physicalization of the nodes and elements allowed entrepreneurs to design while assembling a working prototype of the solutions.

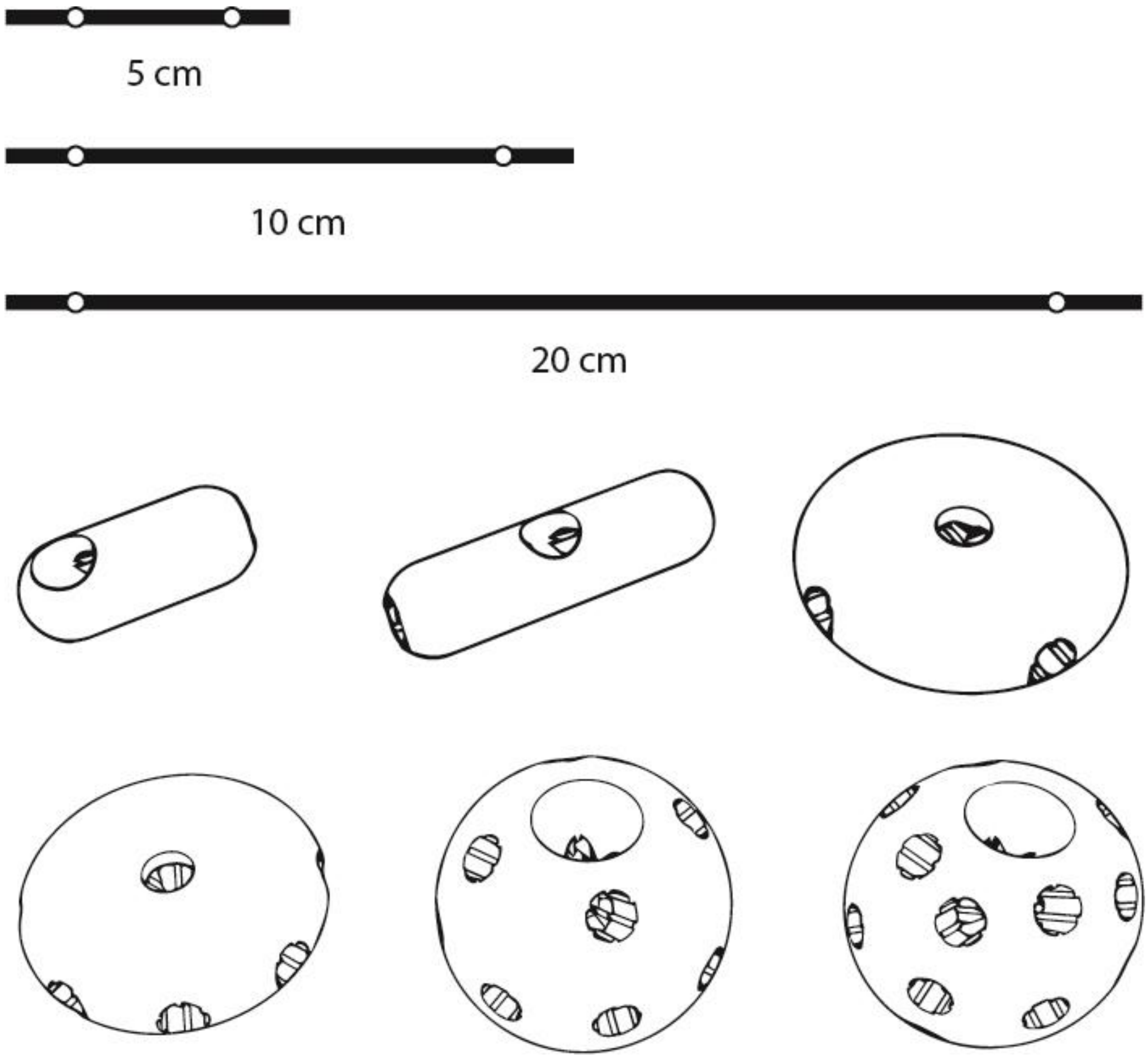


Figure 4.1. The building system was composed by two different groups of elements: joints and poles. Joints increment in complexity while poles increment in size.

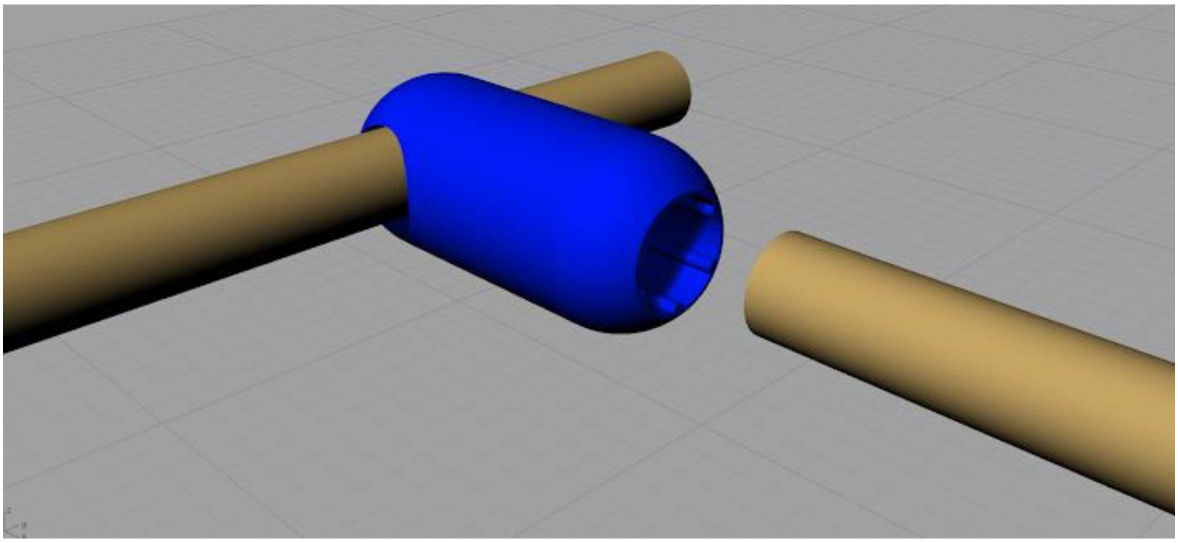


Figure 4.2. detail of the assembly of poles and joints.

The building system was composed by two different building elements (Figure 4.1 and Figure 4.2). The first kind depicted the amount of material used in the solution. These elements are sets of wooden bamboo sticks of 5, 10, and 20 cm long. The second kind manifests the complexity of the connections between components and is represented by 3D printed joints of varying complexities. In order to increase complexity, the joints provide extra slots to attach more poles. The increment in slots provides more directions by opening extra spatial axes to each connection.

Size of pole	Traditional Manufacturing Cost	Additive Manufacturing Cost
5 cm	₸67.02	₸828.26
10 cm	₸134.04	₸1,656.52
20 cm	₸268.08	₸3,312.00

Table 4.1. Cost comparison of building elements in traditional and additive manufacturing scenarios.

Number of slots	Planes	Traditional Manufacturing Cost	Additive Manufacturing Cost
2	X	₸33,056.06	FREE
3	X	₸66,112.12	FREE
5	X,Y	₸132,224.24	FREE
9	X,Y	₸264,448.48	FREE
17	X,Y,Z	₸528,896.96	FREE
25	X,Y,Z	₸793,345.44	FREE

Table 4.2. Increments in complexity and cost of building joints.

The building kit also provided digital spreadsheet that helped entrepreneurs calculate the cost of the designed artefact as shown in the two different brief versions. In the brief provided to the control group, the poles that represent amount of material have low costs that increment proportionally (Table 4.1) and complexity blocks that increase according to the number of axes (Table 4.2). The cost of connector elements for the control group is paid once for each new level of available connections. These traditional manufacturing costs favour design that exploit economies of scale. Differently, the brief used by the experimental group has a higher material cost that corresponds to the need of material processing for AM (Table 4.1). According to complexity freedom, the cost of the joints is free for the groups using AM briefs (Table 4.2). The costs for both material and connector elements were drawn and adapted from a comparative study between traditional and additive manufacturing in the fabrication of aerospace components (Atzeni & Salmi, 2012).

Component 1		Unit Costs		
Responsible partner:	Miguel	Unit 1:	4	units
Name of component:	Catch	Unit 2:	0	units
How does it work?		Unit 3:	0	units
			₸268.08	Material Cost (MC1)
		Max Connection level	793345.44	Complexity Cost (CC1)
	It holds the ball and the Slider			
Manufacturing process	**AM**	Available component production:	1703	units

Figure 4.3. Scheme of the spreadsheet used to describe the architecture of each component. The spreadsheet was structured to help participants calculate their cost and production.

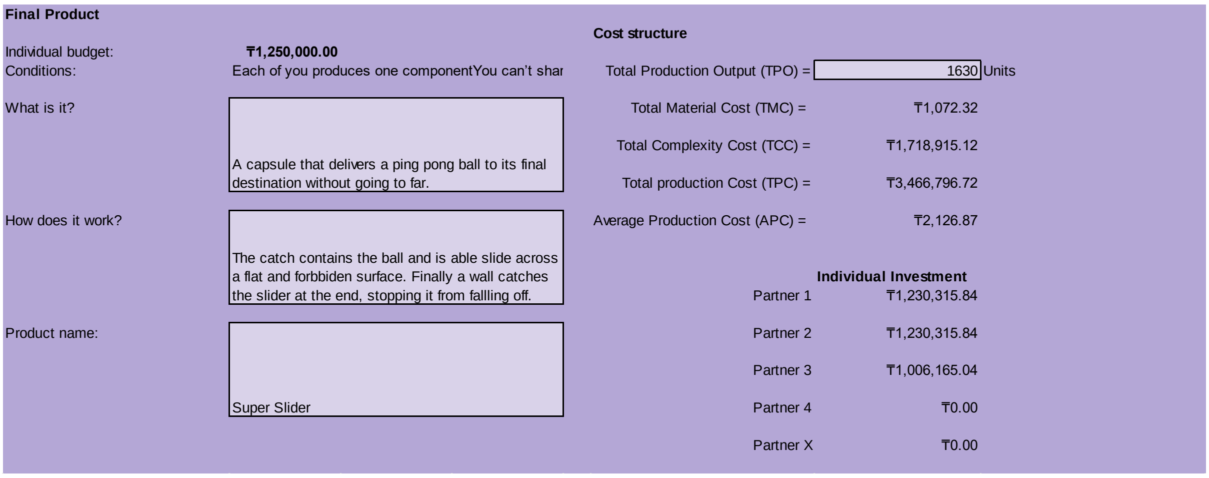


Figure 4.4. Scheme of the spreadsheet used to summarise the final solution of each team.

The spreadsheet that complemented the building set was composed by two sections: individual components and complete product descriptions. The section used to describe individual components registered a name for the participant, the description of the component, and a cost column (Figure 4.3). The cost column was designed for the participants to insert the number of poles used and the greatest joint degree. With this information, the spreadsheet gave participants the cost of each unit and the available production according to their budget. The section in charge of the complete product had a column for the description of the final product and a column with a financial summary of all the decisions made (Figure 4.4).

4.3 Participant Profile and Recruitment

The creation theories of entrepreneurship and product architecture consider the creation of an opportunity as a social enactment. Consequently, the incorporation of the knowledge of other stakeholders has been a priority in the design of the research method. Initial iterations attempted to motivate entrepreneurs to imagine possible stakeholder inputs while creating the product. This produced mixed results. While some entrepreneurs would bring some productive examples, most would bring generic interpretations or stereotypes that did not relate completely to the exercise. Thus, the experiment turned towards team collaboration with the objective of simulating early associations instead of just imagining them. The live interaction with partners also accelerated the design processes, reducing the time entrepreneurs spent on assumptions.

Additionally entrepreneurship research has long debated if a difference exists between entrepreneurs and non-entrepreneurs (Gartner, 1988). Meta-analysis of such research demonstrated that individual traits cannot predict entrepreneurial intention in themselves since they interact with contextual variables (Davidsson, 2007; Rauch & Frese, 2007). The role of the entrepreneur here is better described as the exploration of the means at hand to create meaning out of them (Sarasvathy, 2004). Thus, if the explanation of entrepreneurship behaviours is not in individual differences, sampling could consider any person as long as they are capable and motivated to provide quality data (Davidsson, 2016). Hence, participant recruitment focused on individuals that show some interest in starting business ventures. Knowledge of entrepreneurship jargon and process was considered favourable for the participants to have.

Recruitment was conducted through entrepreneurial clusters or HUB's. Entrepreneurial clusters are organizations or projects within organizations that work with entrepreneurs, designers, and start-ups in the creation of innovative projects. The recruitment of participants consisted of invitations through the heads of the clusters they belonged to. Addressing participants through these HUBs helped the researcher contact potential participants under the data protection guidelines of the Auckland University of Technology Ethics Committee (AUTEC). During a subsequent visit, the researcher exposed the motivations of the project, the mechanics of the kit, and the dynamics of the session. No payment or remuneration was offered besides the availability of the researcher to cooperate and expose a research summary of the use of AM. Afterwards, electronic or printed invitations were delivered with information sheets that addressed the details of the proposed sessions, the experiment, and how to enrol. An auxiliary webpage and a blog were setup under the title "The Firm and the Product" to inform more about the research project and invite potential participants (www.thefirmandtheproduct.wordpress.com). Auckland University of Technology Ethics Committee (AUTEC) approved the complete recruitment process.

4.4 Implementation of the Design Task

Team No.	Number of Participants	Simulated Manufacturing Conditions
1	4	AM (experimental group)
2	4	Traditional (control group)
3	4	Traditional (control group)
4	4	AM (experimental group)
5	3	Traditional (control group)
6	5	Traditional (control group)

Table 4.3. Composition of participant groups.

The study was implemented in three sessions of two hours each. 24 entrepreneurs of ages 20 to 51 participated in this exercise. Despite all of them came through entrepreneurial HUB contact, the degree of involvement with entrepreneurship varied more than expected since some of them had intentions to start a new firm, while others were working or had worked with entrepreneurial firms. Nine of them were women while fifteen of them were men. At the start of the workshops, the researcher introduced participants to the objectives of the study and discussed the ethical concerns with them. Later, participants were told to group to implement the study method (Table 4.3).

4.4.1 Observed material use.

Building Block	Simulated Manufacturing Conditions	Mean	Std. Deviation
5 cm (M1)	AM	5.00	8.159
	TM	2.13	1.857
10 cm (M2)	AM	2.63	2.446
	TM	1.25	0.931
20 cm (M3)	AM	2.88	4.518
	TM	0.75	1.065
Total (MT)	AM	10.50	6.188
	TM	4.13	2.156

Table 4.4. Mean individual number of elements used according to fabrication process "M".

The use of elements that are equivalent to raw material, or material volume, was measured counting the number of units used in each component by size by each participant. The first analysis of material use compares the control and the experimental group. Averaged, individuals working with AM made use of more than twice (+154%) the number material elements (MT) (Table 4.4). However, the variance observed here in the standard deviation is also greater, showing almost three times the variance present in the control group (+187%).

Building Block	Simulated Manufacturing Conditions	Mean	Std. Deviation
5 cm (m1)	AM	5.00	8.159
	TM	2.13	1.857
10 cm (m2)	AM	5.25	4.892
	TM	2.50	1.862
20 cm (m3)	AM	8.63	13.553
	TM	2.25	3.194
Total (mT)	AM	18.88	11.357
	TM	6.88	4.015

Table 4.5. Mean normalized size of elements used according to fabrication process "m".

The number of elements was also normalized according to their size to properly evaluate the total material of each component and compare it with the number of elements in the system. The normalized material quantity increases proportionally for each element size (5cm = 1X, 10cm = 2X, 20 cm = 4X). Accordingly, the total size (mT) should compensate for components with less elements but with bigger sizes. The total size of each component had a similar difference between the two fabrication processes with 174% increase in the total average mass of the components. There was also a 182% increase in the standard deviation between the two processes (Table 4.5) showing that the teams using AM fabricated components with more elements and bigger sizes.

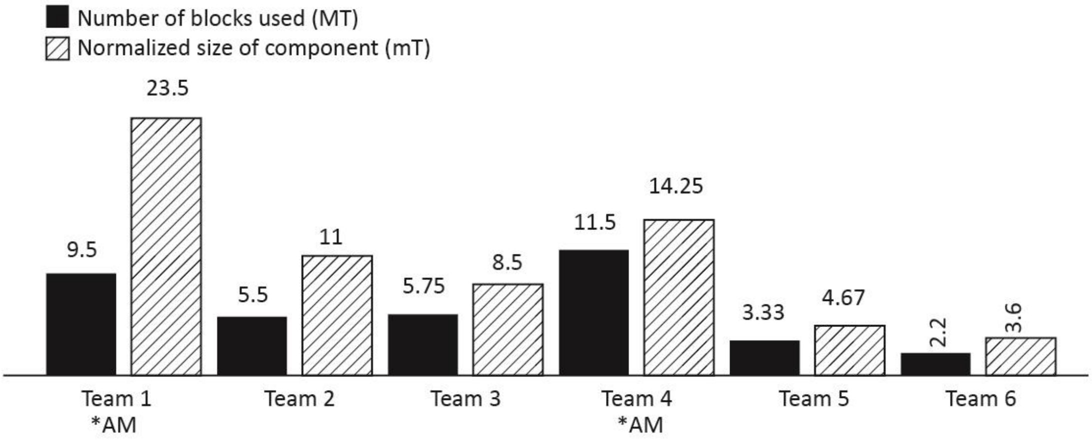


Figure 4.5. Material distribution across teams.

Amongst groups, the use of material clearly differentiates the groups that used AM as a fabrication condition form the others (Figure 4.5). Both Team 1 and Team 4 lead scores in average number and size of elements for each component. However, both groups made a very different use of the building elements with a more balanced use of material in Team 4. At the same time, the use of elements in the control group seems to split sizes in medium (Team 2, Team 3) and small (Team 5, Team 6) solutions. The size of the groups does not affect the size of the solution.

Building Block	Variance Assumptions	t	Sig. (2-tailed)	95% Confidence Interval of the Difference	
				Lower	Upper
M1	Equal variances assumed	1.369	0.185	-1.481	7.231
	Equal variances not assumed	0.984	0.356	-3.965	9.715
M2	Equal variances assumed	2.011	0.057	-0.043	2.793
	Equal variances not assumed	1.535	0.163	-0.689	3.439
M3	Equal variances assumed	1.820	0.082	-0.269	4.546
	Equal variances not assumed	1.312	0.229	-1.663	5.913
MT	Equal variances assumed	3.757	0.001	2.856	9.894
	Equal variances not assumed	2.829	0.023	1.164	11.586

Table 4.6. T-test for equality of means for metrics of total number of elements (M).

Building Block	Variance Assumptions	t	Sig. (2-tailed)	95% Confidence Interval of the Difference	
				Lower	Upper
m1	Equal variances assumed	1.369	0.185	-1.481	7.231
	Equal variances not assumed	0.984	0.356	-3.965	9.715
m2	Equal variances assumed	2.011	0.057	-0.087	5.587
	Equal variances not assumed	1.535	0.163	-1.377	6.877
m3	Equal variances assumed	1.820	0.082	-0.887	13.637
	Equal variances not assumed	1.312	0.229	-4.990	17.740
mT	Equal variances assumed	3.842	0.001	5.523	18.477
	Equal variances not assumed	2.899	0.020	2.462	21.568

Table 4.7. T-test for equality of means for metrics of normalized size of the component (m).

The comparison between the two fabrication methods was statistically tested for variation across manufacturing process using the individual scores. Two 2-tailed T score analyses were implemented for the average number and size of elements (“M”,“m”). Since the study has an inductive approach, both assumptions for equal and different variances were considered. The analysis shows that there is no significance in the average number of elements for each specific kind of building block. The difference of the total number of elements in each component is clearly significant with scores of 0.001 and 0.023 for equal and different variance assumptions in favour of the use of AM (Table 4.6). The average component size “mT” also shows significant scores with 0.001 and 0.020 respectively (Table 4.7).

Building Block	Variation	F	Sig.
M1	Between Groups	2.342	0.084
M2	Between Groups	3.824	0.016
M3	Between Groups	2.014	0.125
MT	Between Groups	3.255	0.029

Table 4.8. ANOVA test for metrics of total number of elements (M).

Building Block	Variation	F	Sig.
m1	Between Groups	2.342	0.084
m2	Between Groups	3.824	0.016
m3	Between Groups	2.014	0.125
mT	Between Groups	4.730	0.006

Table 4.9. ANOVA test for metrics of normalized size of components (m).

A single ANOVA test revealed a significant difference in the total number of used elements and sizes between the teams in the extremes of the group sample (Table 4.8 and Table 4.9). A Post Hoc Tukey test shows that the significant score belongs to the difference in the number of used elements presents between Team 1 and Team 5 in the use of poles in the second category of 10 cm (M2) ($p=0.010$). The same test also shows a relevant F score in the total size of components (m) where Team 1 also has a significant score when compared with Team 5 and Team 6 ($p5 = 0.020$, $p6 = 0.004$).

4.4.2 Observed complexity.

	Simulated Manufacturing Conditions	Mean	Std. Deviation
Complexity degree	Between Groups	2.342	0.084
	Between Groups	3.824	0.016
Interactivity score	Between Groups	2.014	0.125
	Between Groups	3.255	0.029

Table 4.10. Mean scores for complexity degree of joints and artefact interactivity

The maximum level of complexity building blocks was recorded for each participant. Additionally, an interactivity score was given to each component to classify the suggested affordances and add perspective to the use of the connection blocks. The three levels described in Kannengiesser & Gero (2011) were used as a guide to rate the interactivity of each component (1 – 3) and compare it with the maximum degree of component complexity. Participants with AM conditions have higher mean scores for both metrics than the ones with traditional manufacturing conditions (Table 4.10). The average maximum complexity degree used by AM participants is higher by 28%, with a smaller standard deviation by 36% compared to participants with traditional manufacturing sets. On the other side, the suggested affordance interactivity rates are also higher with an 18% increase in average and a 20% increase in the standard deviation. Both scores suggest that participants that used AM used joints of greater complexity in every component but concentrated interactive functions for the user in few components.

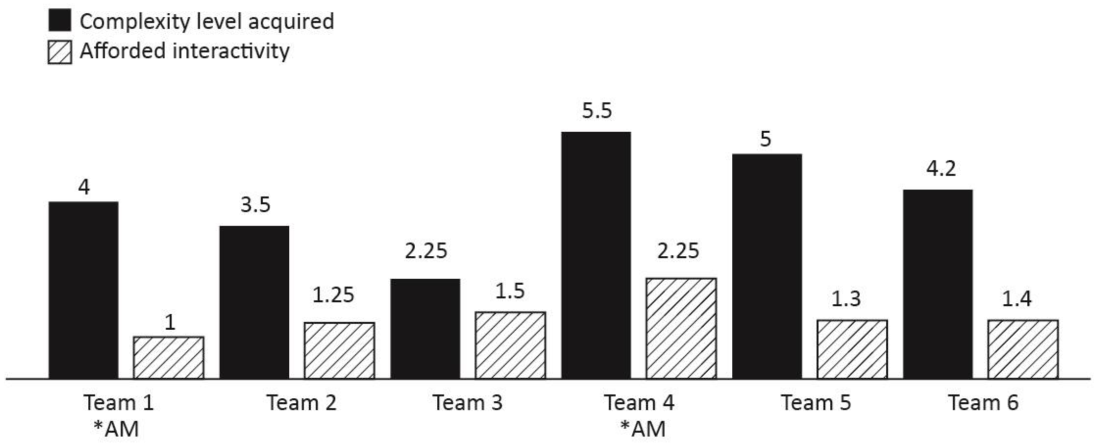


Figure 4.6. Mean complexity and interactivity scored across groups.

Team scores do not show a clear difference between groups for complexity and interactivity metrics (Figure 4.6). Interestingly, three out of six teams used the maximum level of complexity in at least one of the components. However, groups using AM did not use the top level of complexity despite having complexity freedom. Interestingly, both made a very different use of the joints. While Team 4 has the highest complexity average with a score of 5.5 out of 6, Team 1 occupies the fourth place with a score of 4 behind Team 5 and Team 6 that have the lowest scores in material use. Groups using AM material occupy the two extremes of the interactivity scores, where Team 4 delivered a reflective solution, while Team 1 delivered a reflexive solution that has a very limited interaction with the user.

	Variance Assumptions	t	Sig. (2-tailed)	95% Confidence Interval of the Difference	
				Lower	Upper
Complexity degree	Equal variances assumed	1.499	0.148	-0.407	2.532
	Equal variances not assumed	1.734	0.098	-0.215	2.340
Interactivity score	Equal variances assumed	0.873	0.392	-0.344	0.844
	Equal variances not assumed	0.819	0.429	-0.415	0.915

Table 4.11. T-test for equality of means for complexity and affordance degrees achieved by each team.

	Variation	F	Sig.
Complexity degree	Between Groups	5.082	0.087
Interactivity score	Between Groups	0.718	0.123

Table 4.12. ANOVA test for metrics of complexity and interactivity.

The 2-tailed statistical analysis confirms the lack of differentiation between the experimental and control groups (Table 4.11). Once more, the analysis considers both equal and different assumptions on population variances. None of the parameters surpasses the required significance threshold of p = 0.025 showing no significant differentiation between the conditions of complexity freedom and the use of more complex joints or the ideation of more interactive solutions. Furthermore, the ANOVA analysis of the differences between teams shows no statistical relevance for both scores (Table 4.12).

4.4.3 Economic metrics.

	Simulated Manufacturing Conditions	Mean	Std. Deviation
Max. Availiable Production	AM	107.21	68.79
	TM	2580.23	1908.412
Total Production Output	AM	46.0	17.105
	TM	1634.50	451.198
Individual Investment	AM	₸ 739,119.87	₸ 428,824.09
	TM	₸ 1,023,199.78	₸ 279,006.34

Table 4.13. Average economic metrics for available production output, total production output, and individual investment.

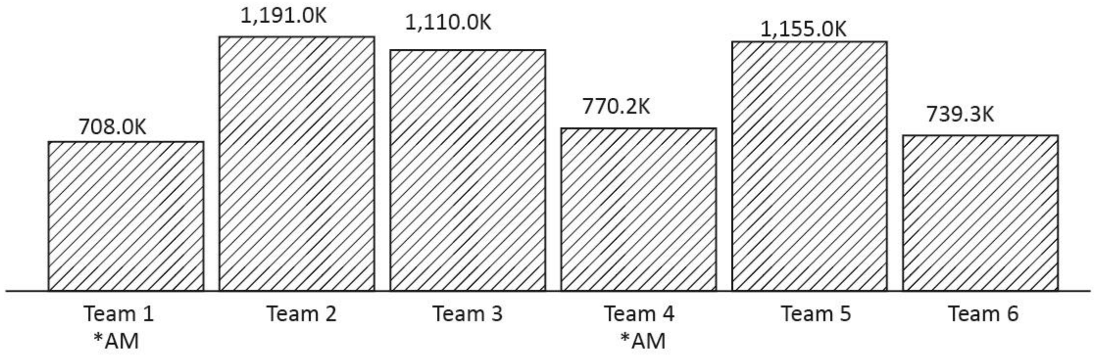


Figure 4.7. Average individual investment across groups.

The gathered economic data showed the expected difference between the implementation of AM and traditional economies of scale. Participants in AM teams had an averaged installed capacity equal to the 4.1% of the averaged capacity in the experimental group. In the same fashion, the relationship between the utilized capacity and the maximum available capacity of the involved partners was also smaller. AM participants managed to capitalize 42.9% of the total production capacity on average in front of 63.3% of those in control conditions. Moreover, the average individual investment was 28% smaller in the case of AM. Together these basic economic metrics show that teams are restricted to the production of the most complex component. That restriction is greater in teams with AM (Figure 4.7) who concentrated most of the investment in some components rather than others, thus restricting the total production output.

	Variance Assumptions	t	Sig. (2-tailed)	95% Confidence Interval of the Difference Lower	Upper
Initial Investment	Equal variances assumed	-1.964	0.062	-₸584,057.12	₸15,897.30
	Equal variances not assumed	-1.702	0.119	-₸655,596.99	₸87,437.17

Table 4.14. T-test for equality of means in individual investment across groups.

	Variation	F	Sig.
Initial investment	Between Groups	2.021	0.124

Table 4.15. ANOVA test for metrics of initial investment.

The evaluation of the investment statistics does not show that the difference between the means of the two groups is significant. The comparison between participants in the experimental and control conditions does not reach the minimum significant level for the 2-tailed prediction (Table 4.14). In addition, the ANOVA analysis does not demonstrate a significant difference between groups with a value of p = 0.124 (Table 4.15).

4.4.4 Qualitative comparison of ideation results.

The development of the objects went through a similar process in all teams regardless the change in experimental conditions. Initially, participants experimented with the ball and discussed the possible mechanics to propel it to the other edge of the table. Discussions were followed by brief brainstorm sessions where one or several solutions were accepted. Next, teams split usually in two or three groups to prototype components that were tested alone. Approximately after 40 minutes, solutions were initially tested as a whole. After these initial tests, teams would select one solution and continue adjusting the effectiveness of that solution until the end of the exercise. During this adjustment, they would organize the final component configuration of the product. Among the six teams, just Team 4 decided to keep the two prototyped versions of the solution as part of the final product.

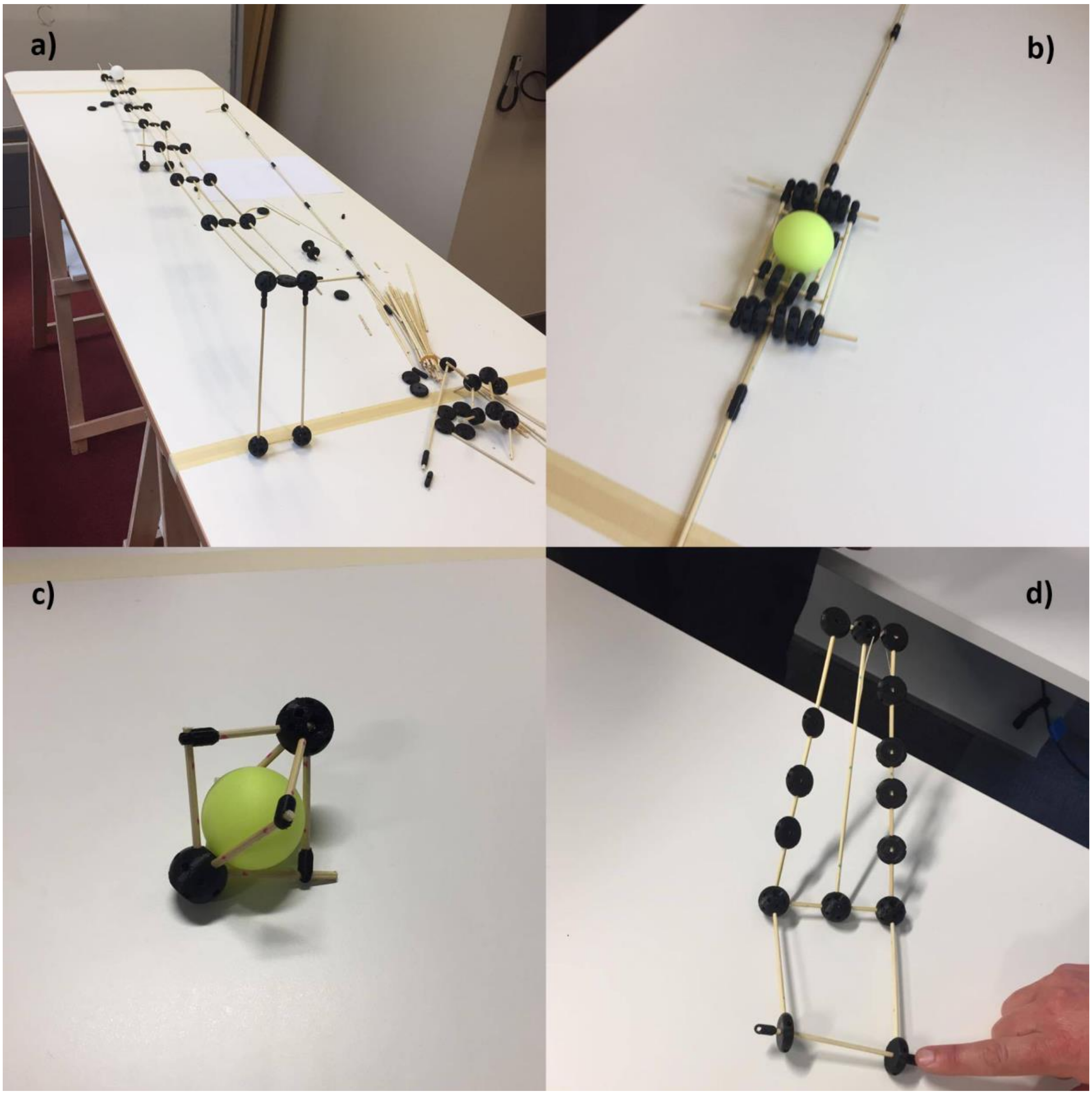


Figure 4.8. Examples of a bridge a), a cart with rail b), a capsule c), and a catapult d).

The discussed ideas within teams fell in one of the following categories: bridges, rails, carts, capsules, and catapults (Figure 4.8). The design of the five options corresponds to the material and complexity use shown in the previous section. Teams with more complex solutions clearly provide higher degrees of interactivity. First, bridge ideas were common during brainstorming but proved to be material intensive and consequently expensive. This is demonstrated by the final artefact produced by Team 1. Bridges provide a limited interactivity since the user only positions the ball and lets the ball slide using gravity. Bridge components are merely reactive since the assembly and installation of the solution does not require user input. Next, participants used rails to guide the ball, a capsule, or a cart to the other end by pushing it or hitting it with another component giving a greater level of interactivity. Rails proved to be very unstable and were not chosen as a final solution by any team. Carts provided more interactivity where users had to aim and push the artefact. Yet, the complexity of functional requirements for keeping momentum and stability seemed to require more material and discouraged some participants. Capsules became the simplest solution to the problem since they complied with the requirements with minimum material. Capsules were complemented with partial rails, barriers and paddles to hit or push them through. Capsules show a higher reactive interactivity where the user oversaw the exact amount of force in the capsule toss. Finally, catapults of launching devices were the most difficult solutions to materialize but the most interactive, they allowed users to play with the position of the artefact, the force used for shooting the ball, and the landing phase as part of the game. Launching the ball required an aiming function that became difficult to develop under the exercise circumstances. Catapults were developed with and without movable parts by Team 2 and Team 4. Most of the teams experimented with several of these solutions, yet no architecture was repeated.

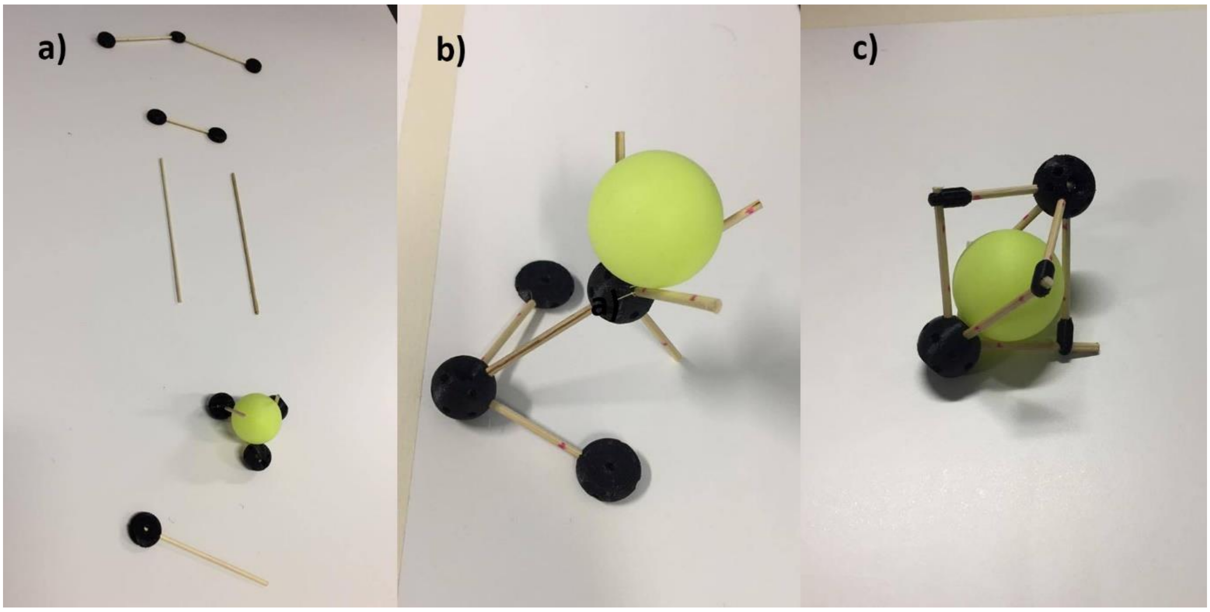


Figure 4.9. Complete solution for team 6 a), launcher designed by team 4 b), and capsule designed by team 5 c).

The brief and the spreadsheet included cost information for the participants to inform the decision-making process. Yet, participants did not seem to consider cost information as a core part of the team strategy. Observations and evidence from the left material rarely found proof of re-calculations of the prototype iterations that appeared through the process. Occasionally few partners within the team would try to work an initial calculation but were later absorbed by the prototyping activities. Moreover, teams seemed to reconsider costs once they were mostly satisfied with the function of their artefact. This led teams to adjust the architecture of their solutions at the end of the period, often stripping down components to the most minimum version. Team 6 is a very good example of this effect where some components of the final version of the artefact were stripped down (Figure 4.9 a).

Amongst all teams, Team 4 stood out for their different approach to the challenge. From the very beginning, the team settled the goal of throwing the ball across and each member prototyped diverse solutions for throwing (Figure 4.9 b). During this iteration process, the team developed the idea of involving more than one user in the reception of the ball. Consequently, their final version was the only one that exploited the space created by the unknown information in the brief. As mentioned above, Team 4 made use of two versions of the launcher - catcher pair, thus offering a set that could expand its use to different games outside the brief. Their performance is the only one nearest to the definition of an effectual process amongst the participant groups. However, it is not possible to connect it to the presence of AM since Team 1 also used an AM kit and designed a product with similar features to the rest of the teams. Moreover, the performance of Team 5 stood up for the combination of high-level complexity blocks and efficient use of material blocks for cost reduction. The capsule architecture in Team 5 proved to be the more effective and complex architecture in the control group (Figure 4.9 c). The contrast between all the solutions and their scores does not support the influence of complexity freedom in the afforded ideas.

4.4.5 Limits of the study.

The design of the experiment used the configuration of the exercise to minimize the influence of design interfaces such as CAD software or design functional matrixes. However, the observed differences in the way teams approached the design of their final solution raises concerns about the role of design expertise in the understanding and mapping of functional requirements. The study has limited means to control for the design expertise of the participants and accordingly, Study 2 aimed towards the simplification of the design task to reduce the impact of design expertise.

The design conditions proposed in this study simulate the internal exploration of the solution within a business. Therefore, the study could be enriched by adding a simulation of stakeholder/consumer response that has a strong influence in the creative process and is absent from this study. Additionally, compliance with AUTEC regulations restricted the use of videotaping and the capture of personal data that could be used in analysis. The activity was designed to be implemented in entrepreneurial HUB's such as accelerators, or co-working spaces. These conditions restricted data collection in exchange for more opportunities for participant recruitment. Further iterations of the same study could look for a more controlled location where more data could be captured without putting participant privacy at risk.

4.5 Study Summary

Study 1 looked for the effects of possible affordances in complexity freedom in the ideation of business opportunities. The study presented a building set and a financial scenario to teams between 3 and 5 participants. Teams were separated in control and experimental conditions. The control group used a building set that followed the logic of traditional manufacturing. The experimental group used costs that belong to the implementation of AM. Participants in the experimental group used more components in the construction of their solution. No significant differences between control and experimental group were found. Observations of the design processes suggest that functional mapping to components is not a priority until the final solution is chosen. Therefore, teams iterate conceptual solutions until one of them is selected. Participants designed solutions that fell in one of five categories: bridges, rails, carts, capsules and catapults.

5 Study 2: Analysis of Semantic Networks

Results of the simulation of *entrepreneurial ideation* in the previous study showed that differences between groups with and without *complexity freedom* were not significant enough to claim that *Additive Manufacturing* (AM) affords greater opportunity complexity. Moreover, observations during the workshop sessions showed little evidence of participants evaluating the allocation of functions in the product they developed. Discussions amongst team members focused more on the functions of the final solution without paying attention to the system level of the product architecture. Such observations raised questions about the assumptions in product architecture research that suggest that the subdivision of the product architecture emerges directly from the subdivision of the requirement functions (Conway, 1968). For this purpose, a decision was made to implement a different method that would simplify the design task in order to corroborate the lack of affordances in the complexity of the means for ideation.

Study 2 looked for a snapshot of the early stage of entrepreneurial ideas and the relationship with the complexity of the ideation stimuli. Based on the literature on creative cognition (Athavankar, 1997; LeBoutillier & Marks, 2003), the task restructures the design process with a mental imagery exercise. Mental imagery is an exploration exercise where creative cognition evaluates different senses of a provided stimuli. Mental imagery has been studied widely as an elemental process in the generation of ideas inside creative tasks (Jankowska & Karwowski, 2015; Kudrowitz & Dippo, 2013). The Geneplore Model proposes that through mental imagery, creative thinking discovers additional emergent features through the mental exploration of unfinished models (Finke, 1996). Mental imagery removes the medium used for the implementation of the participant’s ideas and thus, reduces the influence of variables that correspond to design expertise. The study hypothesis is stated as follows:

H. The complexity of product architecture has a mirroring effect on the complexity of the semantic structure of entrepreneurial ideation.

The study presented participants with a visual input of a determined complexity as means for the exploration of a market opportunity. The exercise presents randomly generated images that resemble product-like volumes with variations of complexity and symmetry. The task asked participants to interpret the image as a novel product and complete 13 statements that described the business opportunity. Survey items were designed to bring about mentions of object categories, their features, and the identities of possible actors around them. The categories mentioned in the description were used to study the semantic structure of the opportunity. These categories show a set of sensible meanings that support the effectuation of the opportunity by drawing attention to specific features, objects, identities and institutions that define the environment in which the firm is going to participate. This system of concepts resembles a sample of the use of the artefact in language (Krippendorff, 2006; Lakoff & Johnson, 2008; Spinosa et al., 1995). The study looked for the structural properties and semantic features of this system and compared it to the complexity of the product architecture.

5.1 Survey Items

The design of the survey items looked for a representative sample of important themes that describe the business venture. Nonetheless, since entrepreneurship covers both necessity and opportunity motivated entrepreneurship, there is no evidence that points out a particular or minimum management literacy that unifies themes and concerns in early entrepreneurship activity (Global Entrepreneurship Research Association, 2017). The design of the survey aimed to balance this literacy problem by reviewing two of the most popular works in business modelling popular literature (Osterwalder et al., 2010, 2015), and matching themes with product categories, features, and identities as proposed by product semantics (Krippendorff, 2006). The structure of the items was tested as questions and incomplete sentences with ten participants through an online platform. Tests with questions left space for participants to introduce their answers indiscriminately. Captured answers featured a complex syntax that helped sentence coherence but did not add information to the survey focus. The final version of the survey used an incomplete sentence format that standardized the sentence syntax and guided the participant to introduce the desired content. A complementary parenthesis was added to reinforce the directions.

According to the guidelines proposed by the Auckland University of Technology Ethics Committee (AUTEC), the survey was introduced with a description of the exercise and a following consent form. Next, the survey asked for personal information to control confounding variables such as the domain of English language, the maximum obtained scholar degree, and age. Then, survey instructions and an example were presented. The instructions were introduced as follows:

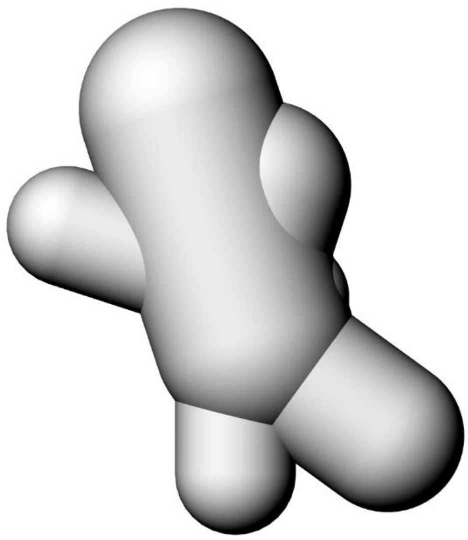
> *You will see a picture of an "abstract product". This abstract product represents the final shape of the product that you are going to use to start a company. The shape is unfinished on purpose. Interpret the*

shape as you like, rotation, size, colour, material and details can be added in your mind to fit the functions that you imagine. The components (bodies) of the form can work separately, they can be detached but cannot be split in themselves.

Take enough time as you need to make up your ideas.

You will be asked to complete some sentences based on your interpretation of the picture.

Example:



Complete the following statement:

The product is a kind of (describe a category)...

...stuffed teddy bear

(Osterwalder et al., 2010)	(Osterwalder et al., 2015)	(Krippendorff, 2006)	Prompt statement
Value Proposition	Value Proposition	Object / Character	The name of the product is (describe a name)...
Value Proposition	Products and Services	Object	My product is a kind of (describe a category)...
Customer Segments	Customer	Identity	My product is designed to assist (describe the customer that will buy it)...
--	Customer Jobs	Activity	My product helps customers to (describe the goals of the costumer)...
--	Gain creators Pain relievers	Activity	My product fulfils these goals by (describe how the product works)...
Incumbent Forces	--	Object	My product competes against other products like (describe other product categories that could compete with your product)...
Value Proposition	Pains and Gains	Object	My product is better than its competitors because (describe the traits or qualities that make it the best option for your customers)...
Customer Relationships	--	Object	The name of my brand is (describe a name)...
Customer Segments	--	Identity	My brand is designed to reach (among your customers, describe the brand lead users/fans)...
Customer Segments	--	Object	My customers believe in (describe the values that your customers believe in)...
Key Partnerships	--	Identity	My brand partners with (describe categories of other firms you could partner with)...
Key Partnerships	--	Activity	Together with these partners we (describe the activities you could do with your partners)...
Distribution Channels	--	Activity	Therefore, my brand delivers our products through (describe your distribution channels or how are your products delivered)...

Table 5.1. Comparison of themes in literature and survey items.

5.2 Shape Generator

Images used to elicit mental imagery in the entrepreneurial ideation exercise showed product-like volumes of different complexity. The images were designed through a generative design shape grammar that used a sequence of steps to randomly allocate components to bodies. The image generator algorithm used a gradient of complexity that only controlled the number of components in product architecture and not their position or orientation. The degree of image specificity avoided the placement of special features like textures or concavities that could remind of specific features such as buttons, triggers, or vents. The images also avoided features that could fixate the participant to a specific scale and production domain.

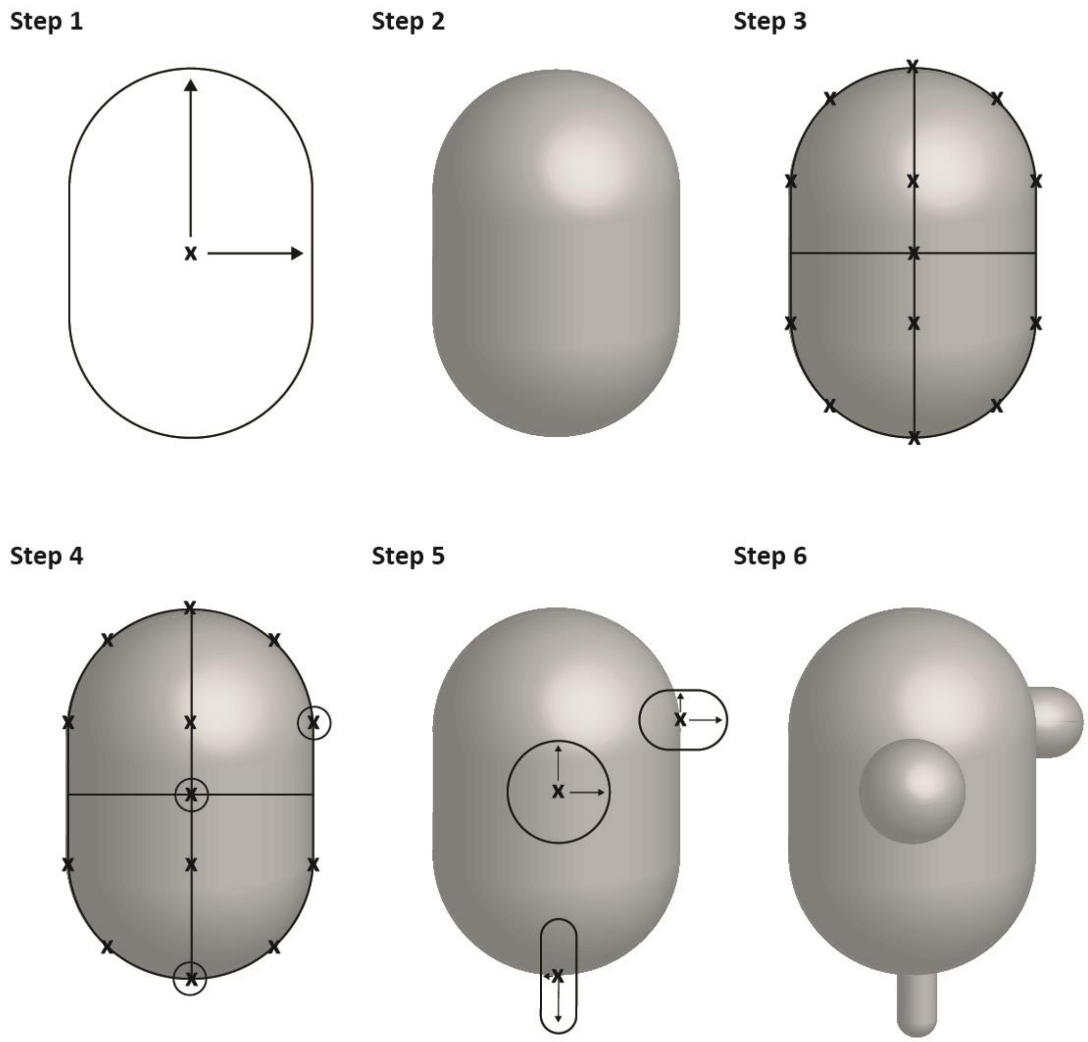


Figure 5.1. Process of image generation.

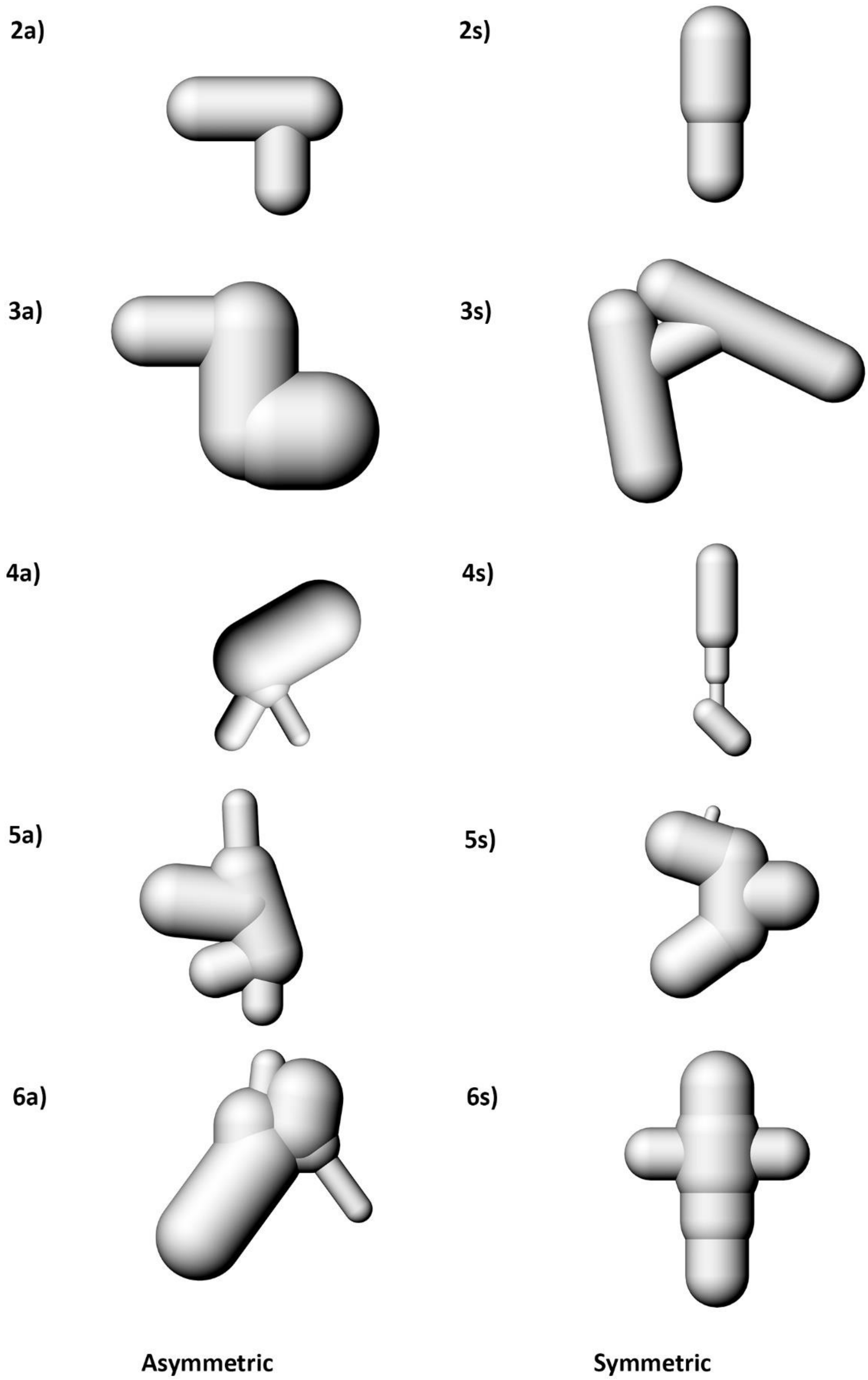


Figure 5.2. Final collection of exercise inputs.

The image generator allocates a specific number of components as follows (Figure 5.1). First, it marks a centre from which it creates an initial revolved volume with semi-random width and length. Next, it creates a guideline structure on the perimeter of the middle section of the volume and the X and Y axes of the same plane. It randomly allocates anchor points into the structure that will serve as centres for other components. Within these points, the grammar randomly selects a number between 1 and the maximum number of desired components as origins for the next group of components. It creates revolved volumes perpendicularly to the centre of the original figure and repeats the same operations until the architecture has the desired number of components. Since the most basic complexity level is made of the interaction between two components, the complexity gradient for image generation included 2-6 components in five levels of complexity. The algorithm created over 50 configurations in each level. Shapes were classified in symmetric and asymmetric categories since both categories can influence perception differently (Dakin & Hess, 1997). The resulting 10 pools of images were submitted to moderation with both thesis supervisors. One representative of each pool was selected. The images were labelled according to the number of components in the architecture and the symmetry condition (Figure 5.2).

5.3 Participant Recruitment

Study 2 had also the purpose of expanding the scope of participant recruitment through an online platform. The selection criteria for participants looked for the minimum age to legally sign up to an online platform, and a minimum high-school literacy for the understanding of the task. The task was designed as an exercise for meaning elicitation of entrepreneurs (Sarasvathy, 2004) and did not consider the existence of individual differences between entrepreneurs and non-entrepreneurs (Davidsson, 2007; Gartner, 1988; Rauch & Frese, 2007). It considers an entrepreneur any person who is capable and motivated to provide quality data. The survey presented an add with a description of the activity and the relevance of the project in order to motivate participants.

The survey was developed through Qualtrics, an online based software for survey design and publishing (Qualtrics, 2014). The survey platform permits participants to join the survey online through any electronic device using a link. After analysing different modes of recruitment, it was decided to hire Amazon's Mechanichal Turk (MTurk) services for the recruitment process. MTurk is an online platform with a marketplace that connects task creators to task solvers in exchange for a remuneration. Creators design tasks in and out the MTurk platform and invite the population through the tools provided by the platform. After solvers finish the task, the creator has the opportunity to revise the provided solutions and authorize remuneration (Amazon Mechanical Turk Inc., 2018). MTurk represents a solution for social scientists that wish to streamline data collection processes. It has been used in online psychological and usability studies and found as valid and effective in comparison with other online recruitment tools (Bunge et al., 2018; Cunningham et al., 2017). Participants have been described as diverse and self-motivated (Buhrmester et al., 2011). However, researchers have also documented that an increasing population of MTurk employees rely on the income they receive through the platform as main income instead of a casual one (Hara et al., 2018). In order to alleviate this, it was decided to recruit participants with a higher rate of $2.40 USD for the 15-minute task against an average of $2.00 USD /hr documented by Hara et al. (2018). The platform provided means to segment the participant population according to their age and literacy.

5.4 NLP Analysis Background and Instrument Design

The Natural Language Processing (NLP) analysis tool was designed with the purpose of visualizing the structure of the semantic network generated in the entrepreneurial ideation exercise. The visualization of this structure discloses the number of elements in the semantic network as much as the relationships that exist between them in a way that can be compared to the complexity of the system level of the product architecture. Such relationships expose the analogical comparisons used in the recognition of the artefact and the exploration of alternative uses (Gentner & Markman, 1997; Murphy & Brownell, 1985). Analogies are cognitive devices that emerge when two situations share relational structure. They build on the recognition of patterns and structures between perceived artefacts and recognized patterns in the user's memory. Analogies prioritize perceived relationships over perceived objects, and therefore allow the comparison of the two systems. The lack of definition of relationships over objects in analogical thinking is important for the recognition of new features in the exploration of mental imagery (Finke, 1996).

The use of analogies in creative ideation has been studied (Linsey et al., 2008). Design research has developed methods for the disclosure and measurement of the similarity between the drawn analogies (Krippendorff, 2006; Osgood et al., 1967; Patwardhan & Pedersen, 2006). These methods are able to determine the semantic "distance" of two terms. Similar analogies are considered to be "near" while those that have no relationships are said to be "far" from each other. The influence of far analogies in design has been corelated to the creation of innovative solutions (Fu et al., 2013). These methods for the measurement of semantic relatedness have also been used to develop NPL applications for Artificial Intelligence that use semantic similarity for word disambiguation in translation and conversational computers (Budanitsky, 1999).

The structure of semantic relationships in language is anisotropic because it builds upon contextualized human experiences (J. J. Gibson, 2014; Hall, 1990). These are static which complicates the measurement of different analogies (Miller, 1995). Therefore, the methods used for the exposure of semantic relationships and the measurement of semantic distance, use existing databases such as thesauri or dictionaries that provide a structure that has already been moderated by an institution. A thesaurus or dictionary is structured by manually coded entailments in the form of lexical-semantic relationships that portrait the state of a language in a particular period of time (Hardeniya et al., 2016). In these databases, words are related through lexical-semantic relationships such as; synonyms, antonyms, etc. This semi-structured blueprint of language provides a system where normalized measurements of similarity can be implemented.

The selection of the structure of the thesaurus and the semantic comparison algorithm are the two main concerns in the implementation of these methods. Thesaurus based NLP toolkits utilize different dictionaries depending on the developed application. The most accessible dictionaries, WordNet, ConceptNet, and Wikipedia are frequent in research projects. WordNet is a large lexical database that contrary to regular dictionaries, organises nouns, verbs, adjectives, and adverbs in sets of synonyms in a machine-readable way to facilitate language processing (Miller, 1995). WordNet's semantic relationships group most of the words in hypo/hypernym relationships, which manages to concentrate the overall structure into 11 basal terms that give it a depth reference point. Similarly, ConceptNet is a database designed to capture common knowledge or the basic meanings, facts, or understandings of regular people (Liu & Singh, 2004; Speer et al., 2017). Contrary to WordNet, ConceptNet does not use lexical relationships but instead a concept called K-lines described as common-sense relationships between concepts like "A is the result of B" or "A is used for B" (Minsky, 1980). ConceptNet occupied an open-sourced strategy to expand its database to other languages besides English and is still in development (Speer, 2017; Speer & Havasi, 2012). Wikipedia works also as a method for semantic disambiguation due to the vast amount of interconnections that have been manually set by contributors (Gabrilovich & Markovitch, 2007; Milne & Witten, 2013). Methods that use Wikipedia occupy texts in the provided articles and the included links with diverse results. The method in the current study used WordNet as database for semantic comparison, because of its standardized use among researchers, the stability of its structure, and the ability to process the database locally.

The analysis tool was built using a python-based Natural Language Toolkit that facilitates analysis with WordNet. The design adapted the existing tools for word disambiguation with WordNet present in the NLP toolkit developed by Bird et al. (2009). In WordNet, the measurements of relatedness and similarity usually consider the “A is a B” relationship to escalate the hypernym structure until a common ancestor is found for the two words. Besides hypernymy WordNet has been expanded with meronymy, toponymy (part of, substance of, member of), synonymy and antonymy relationships. WordNet also has an “entailment” relationship that relates words semantically outside the lexical relationships. The number of “edges” between nodes is used to calculate an average distance that is normalized using the level of abstraction of both terms and their common ancestor (Budanitsky & Hirst, 2006). The method used in this study works with the functions within the toolkit that extract the lexical-semantic relationships. It provides a clear visualization of the interconnectedness between the categories created through the process of analogical thinking in the exploration of entrepreneurial ideation.

The algorithm parses the set of words that come from either a particular sentence or a group of sentences. Next, it transforms them into their recognized form in WordNet (if possible), and assembles a word pool, it counts the number of repetitions of each, and eliminates the repeated ones. Following, it traces all the lexical-semantic relationships and their depth inside WordNet for every word inside the pool and saves two lists: one of node indexes, and one of edges between them. The complete set of relationships traced by the algorithm in the thesaurus create a directed network where edges go from pool words to inferable words.

$$\boldsymbol{\rho} = \frac{|\boldsymbol{E}|}{|\boldsymbol{V}|(|\boldsymbol{V}| - \mathbf{1})}|$$

Equation 5.1. Formula for the calculation of network density (undirected).

Using the pool network, the algorithm makes four calculations: the number of nodes, the number of edges, the density of the network, and the number of contact nodes inside it. The density of the network is a standard measurement in graph theory. It describes the ratio between the exiting edges and all the possible edges between the nodes in the network (Equation 5.1). The algorithm uses undirected density calculations for all networks. In addition to network density, the measurement of contact nodes counts inferable words that are related to two or more concepts present in the initial word pool. Contact nodes represent analogical relationships drawn in the exploration of the image. These nodes are of great importance since they can be used as a proxy measure of the semantic closeness of the whole network. The algorithm finishes by tagging every node for each image it appears in, the number of components of the image, symmetric or asymmetric, and the statement it comes from.

5.5 Results: Quantitative Analysis of Semantic Relatedness

5.5.1 Corpus conditions.

Image	2a	2s	3a	3s	4a	4s	5a	5s	6a	6s
Number of valid participant responses	28	30	35	34	27	33	27	34	28	32

Table 5.2. Number of valid responses per shown image.

The survey was implemented in a weeklong period through the MTurk platform. Overall 586 responses were received and just 360 of them were completed. Participant English proficiency shows that 97.5% of the respondents described themselves as native English speakers leaving only nine respondents who learnt English as a foreign language. From the completed surveys, 52 were found not valid for one of three reasons. First, the survey was filled out with invalid data such as numbers or random letters. Second, the survey was answered with the questions rewritten as answers. Third, invalid surveys were filled out with random data that did not correspond to the questions. Hence, the 308 valid responses correspond to the image distribution as shown in table (Table 5.2). The extracted text form these answers composes the raw text corpus for analysis. The respondent selection was composed of 31.2% of participants that finished high-school, 44.4% of participants that completed a bachelor’s degree while 24.4% had completed a postgraduate degree. The biggest age groups that answered the survey were: 45 years or older (26.81%), 25-29 years (20.48%), and 30-34 years old (17.47%).

Corpus level	Unique words in corpus
Raw text	17766
Syntactic relevance	15186
Semantic relevance	6976
Product categories, identities, and organizations	5504

Table 5.3. Total number of words according to level of classification.

The analysis began parsing the raw corpora in four levels according to their syntactic role and uniqueness in relationship with other responses (Table 5.3). The first corpus of data consists of the raw data as the participant wrote it. This pool contains words with syntactic categories such as articles, adverbs, and functional words that link the sentence and help reading (e.g. because, with, therefore, the, and). Analysing the raw corpus adds noise from functional words to the relevant semantic relationships between the core ideas. The second parsing removed these functional words with NLP tools, leaving the text that is syntactically relevant to the evaluation of the network. Inside this second level of the corpus the coding process found words that create semantic noise for the delineation of each answer. Words such as “new”, “innovation”, “design”, superlatives such as “hyper”, and business generalizations such as “business”, and “retail” were too typical and did not improve the description of semantic relationships.

A third parsing of the corpora included a manual coding procedure referred to a definition of classes drawn from the descriptions of by Krippendorff (2006) and Spinosa et al. (Spinosa et al., 1995). Both works describe the artefact as the source of three main classes, object categories, personal identities, and features or characters. This classification focuses in the definition of “what it is” instead of “what it does” and sets aside adjectives, verbs, and adverbs that can be used in many other contexts. This classification also improves the semantic relationship search inside WordNet by focusing on nouns, which is the more developed collection in WordNet. However, participants sometimes referred to the same concept with other words with the purpose of avoiding redundancy (eg. police officer, officer of the law, officer). Through a last manual coding, problems between expressions that referred to the same concept were settled to the most specific one in the final version of the data corpus. In the same way, this manual coding corrected spelling accidents with clear intent (e.g. officer vs oficer). Additionally, expressions that were composed by two words were joined with an underscore to match WordNet formats.

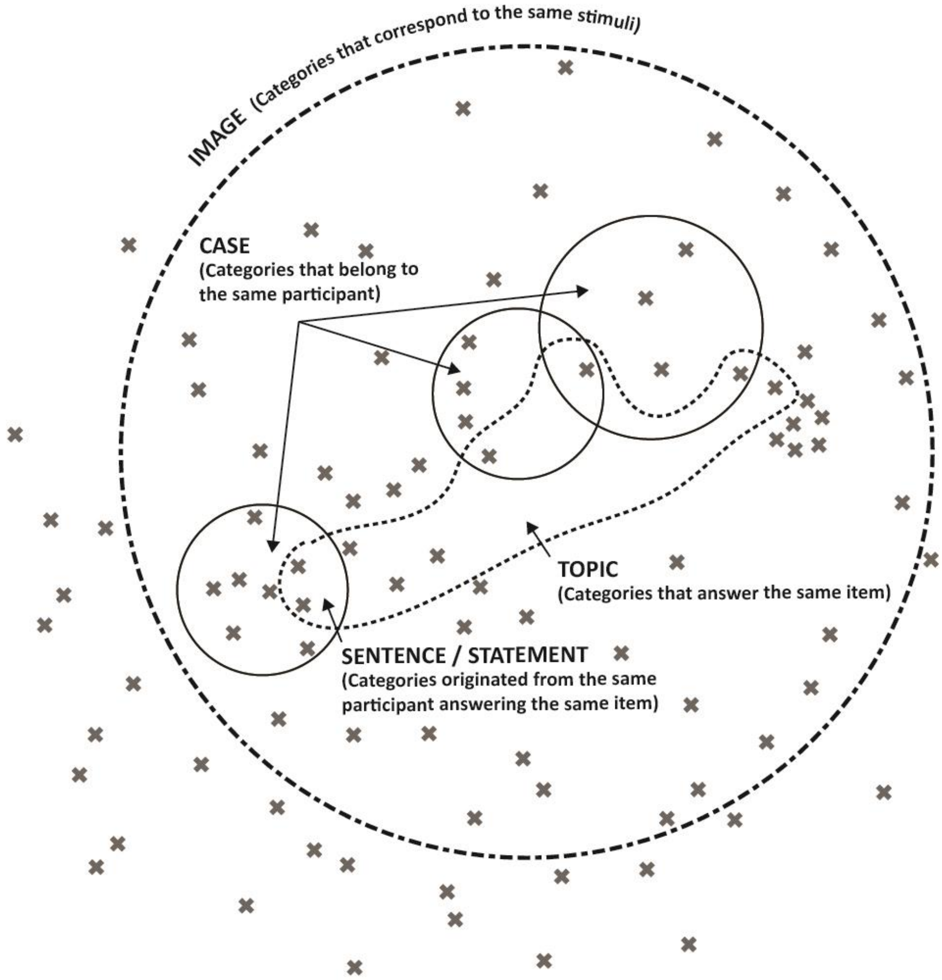


Figure 5.3. Word relationship levels.

Once separated and classified, the analysis of semantic relatedness was held in four different scales (Figure 5.3). These scales corresponded to the available labels in the structure of the survey database: sentence, concept, topic, and evaluated image. The sentence scale gathers all words mentioned in the same individual statement to form a word pool. Sentence scale pools were often small due to the already reduced number of words in the corpus. The corpus contained 4004 pools of sentence level scale. The collection of the 13 pools of sentence-scale statements retrieved from one participant constituted a concept scale. 308 pools of concept scale that correspond to the total number of participants exist within the data corpus. The topic level gathers all the statements that answered to one item across all the participants within the same image (e.g. all statements from image 4a answering item 3 – customer segments). This topic level considers only the answers within a same image to mark differences between images of different complexity. The data set contains 130 topic pools. Finally, the image scale comprised all the statements from all participants that received the same image input. The image level would represent the semantic universe related to a certain stimulus if all the participants were the only stakeholders around it.

5.5.2 Theme classification.

Module	Percent
Games and Toys	22.73%
Gadgets and Electronics	18.51%
Massagers, Sports and Camping	12.34%
Pharmacy and Home Repairs	10.71%
Tools and Furniture	7.79%
Home Shopping	7.79%
Elderly Assistance	7.47%
Hand Graspable and Flexible	6.82%
Stress Balls and other Squeezeables	5.52%
A Chilly Pack for Injuries	0.32%

Table 5.4. Table of themes present in the idea population.

The 308 retrieved answers were manually coded in a parallel process similar to the algorithmic one to get an initial sense of the themes amid them. The categorization used the classes already present in the filtered data of object categories, personal identities, and organizational identities. The most specific object category, personal, and organizational identities were selected manually as a tag for each concept within each class. The tags were connected in each class according to their metonymy and hypernymy relationships together. The connections made through classes built a network composed by grouped clusters of ideas that resemble common themes. The final network of 308 concepts produced 2153 edges between. The network was analysed and modularized using an algorithm used for the localization of communities in complex networks (Blondel et al., 2008). The result presents a collection of modules that resembles themes more than superordinate categories of objects. Nine themes emerged from the clusters generated by the network and just one idea was left out any group (Table 5.4).

5.5.3 Network size.

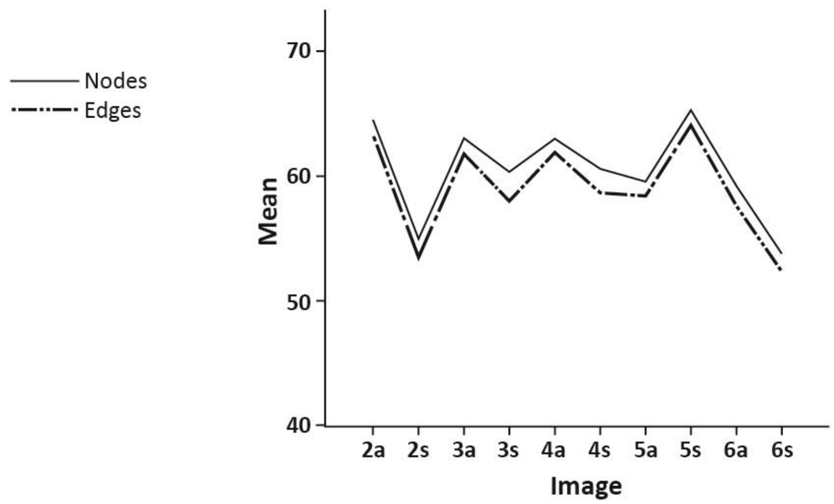


Figure 5.4. Mean network nodes and edges for the sentence level.

Words obtained from individual sentences averaged 2.19 original words per statement. The mean size of the network generated from these sentences averaged 60.45 nodes and 59.03 edges. These networks had a mean 0.46 contact nodes each. This means that words in a sentence level have populated networks of entailments that rarely collide according to the semantic criteria drawn above. Single ANOVA analyses were used to test differences between samples from different images, number of components, and symmetry. No statistical difference was found for total number of nodes, edges, or connections. Similarly, there is no trend in the data that corresponds to increasing complexity degrees (Figure 5.4). An additional review of the number of words in each pool and the frequency of each of the words in each of them did not show any significant difference either.

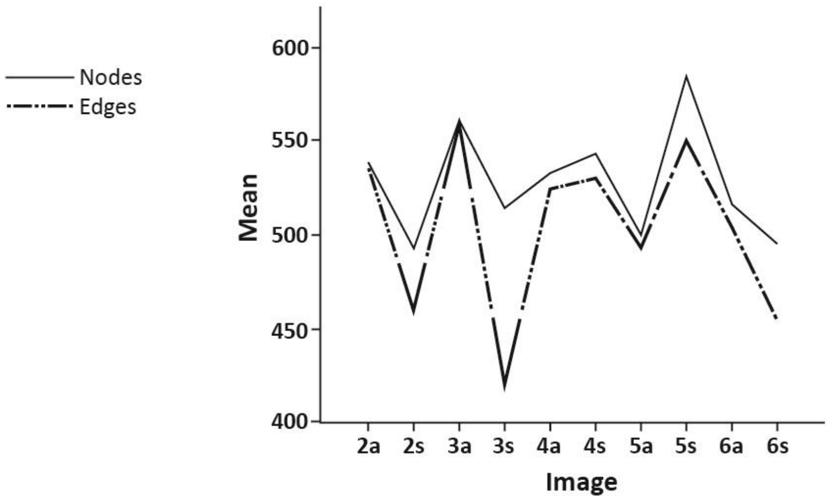


Figure 5.5. Mean network nodes and edges for the concept level.

The concept level presents more interconnections due to the increased number of words in each pool. The mean number of nodes and edges rises almost tenfold with 528.76 nodes and 503.17 edges. Yet despite having a proportionately lower number of edges in comparison with the sentence scale, the number of average contacts increases to 28.82. The similar statistical tests were run with no relevant statistical variance in any of the three metrics for image, number of components, or symmetry. Like the sentence scale, there is no trend in data that aligns with an increase in the number of components per image (Figure 5.5). Moreover, differences between means become wider.

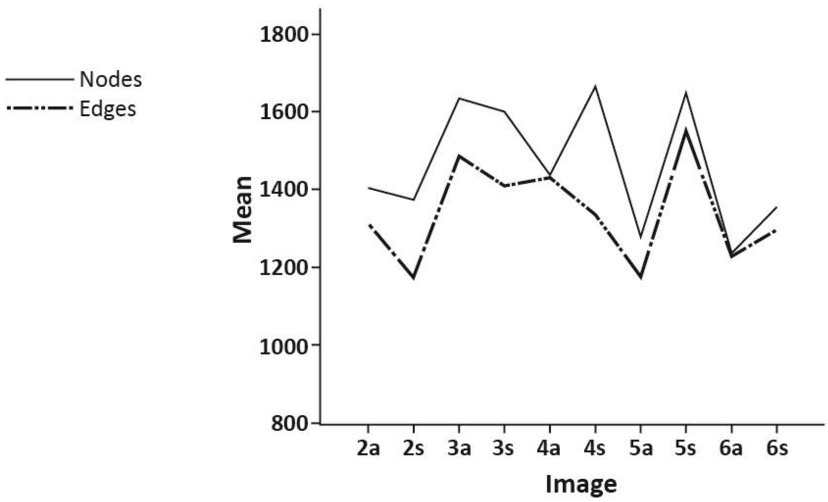


Figure 5.6. Mean network nodes and edges for the topic level.

Topic networks are in average 276% bigger than the concept scale. Topic scale averages 1461.71 nodes and 1341.09 edges. Again, the amount of contact nodes increases to a 105.04 contacts per network. No significant differences between different images, number of components, and symmetry were found. While the trends of both mean number of nodes and edges seemed to be somehow aligned in the small levels, in the topic level they present broad differences (Figure 5.6).

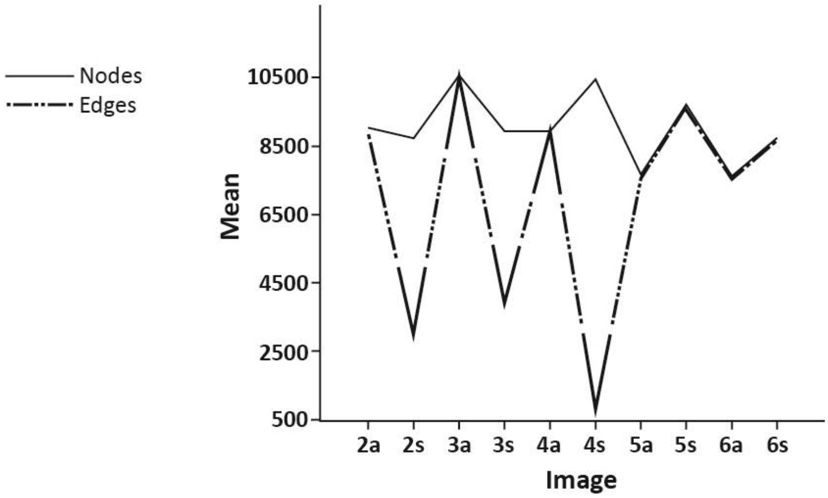


Figure 5.7. Mean network nodes and edges for the image level.

The image scale networks contain 9034.3 nodes and 6984.8 edges per network with an average of 2766.1 contact nodes in each. Once more, data shows no significant difference for changes in image, number of components and symmetry. The partial alignment between the mean number of nodes and edges disappears completely showing that images with the highest number of nodes do not correspond to the higher number of edges (Figure 5.7).

5.5.4 Network density and contact nodes.

The proportion of nodes and edges in each network does not have any correlation with the number of components and the symmetry of the artefact. ANOVA tests show no statistical difference for any α level for any collection of samples: image, number of components, or symmetry. This data shows that participants do not show a greater sum of words or a greater number of connections between them as the complexity of the image increases. Contrary to the gathered data, a positive correlation with increasing complexity would show a trend in vocabularies where the total number, diversity, specificity and the number of entailments change as the complexity of the input increases. An example would show difference between cases that describe a more general superordinate category (e.g. furniture) against cases that describe a more specific subordinate category (e.g. baby stool). Subordinate categories should possess more contact nodes that name more identities, components, or features. Yet data shows no correlation to the complexity of the image. This was corroborated by the measurement of each word's depth (measurement of specificity using the hypernymy-hyponymy relationship) showing no significant differences.

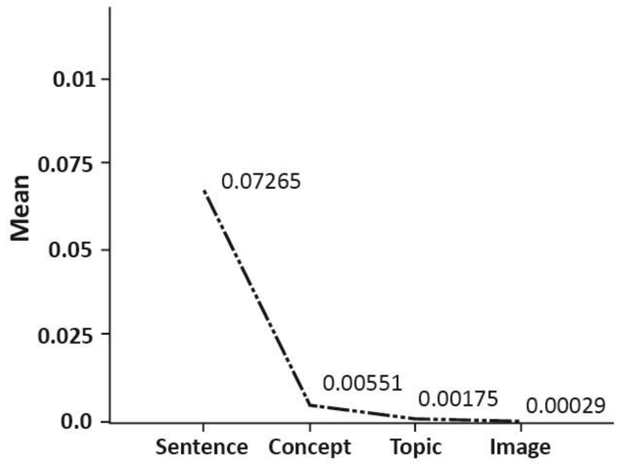


Figure 5.8. Comparison of mean density across network levels.

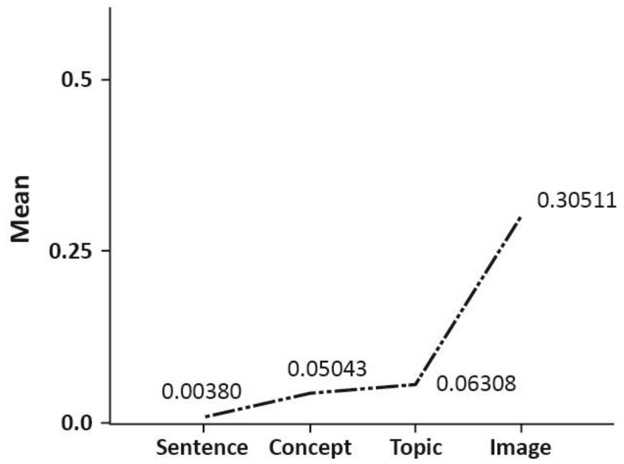


Figure 5.9. Comparison of mean number of contacts across network levels.

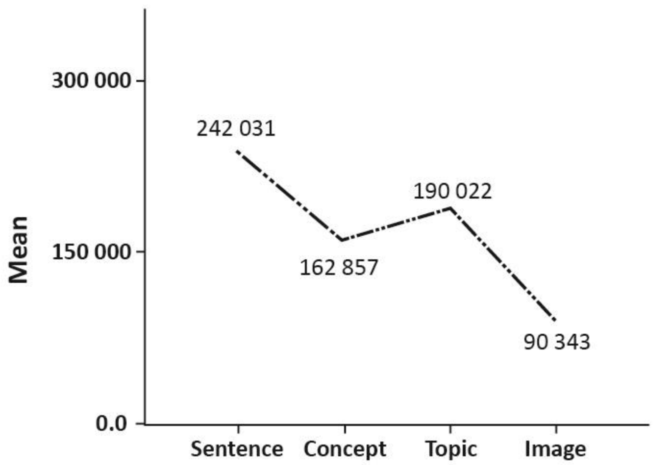


Figure 5.10. Comparison of total evaluated nodes across network levels.

Yet, it was found that the relationships in the statistics amongst the different scales of evaluated networks show interesting insights about the semantic universe around an image. The density measurement considers all the possible connections between all nodes within a network. Accordingly, the mean density of each network is reduced as each scale level grows. Interestingly the opposite occurs with the mean number of contacts per network, which increases proportionally from 0.007% to 30.61% of nodes.

However, the number of processed words in each scale decreases as sentences are incorporated to bigger networks. The reason this decrement is the repetition of words in sentences. This is expected between the sentence and concept scales where the same participant describes the same concept. Within one concept, a participant would repeat one category several times in various sentences, but the algorithm would count it only as one node in a concept level. Yet, a similar degree of word repetition happens in the topic and image scales despite not being originated by the same participant. Therefore, the reduction of evaluated words in such levels makes the increasing number of contact nodes more relevant. These results suggest that as the semantic network grows, there are networks of words that are shared amongst ideas and even amongst images. These networks of words seem to be shared but not always present. This shared language seems not to be affected by the product complexity variables as shown above. Having control over the complexity and symmetry variables of images, the image morphology may be the origin of the shared semantic domain of the answers.

5.5.5 Word by word analysis.

In order to understand these shared semantic networks amongst ideas, the analysis proceeded with an evaluation of the network generated from the complete pool of words from all images. The objective of this review was to obtain a complete image of the connections amongst shared vocabularies used in different images and examine them for an alternative explanation to the affordance of complexity. Each word received a tag for the images it appeared in, number of components and symmetry, in-degree centrality in the word network, and closeness centrality. The complete word network contained 31,493 words. Within those, 2,218 words were retrieved from the survey while 10,380 were contact points between them. These sum 12,598 words that have entailments connected to more than one original word. The cleaned-up network is an incomplete one ($\rho \approx 0$) with 12 edges of diameter and average degree of 3.18 edges per node.

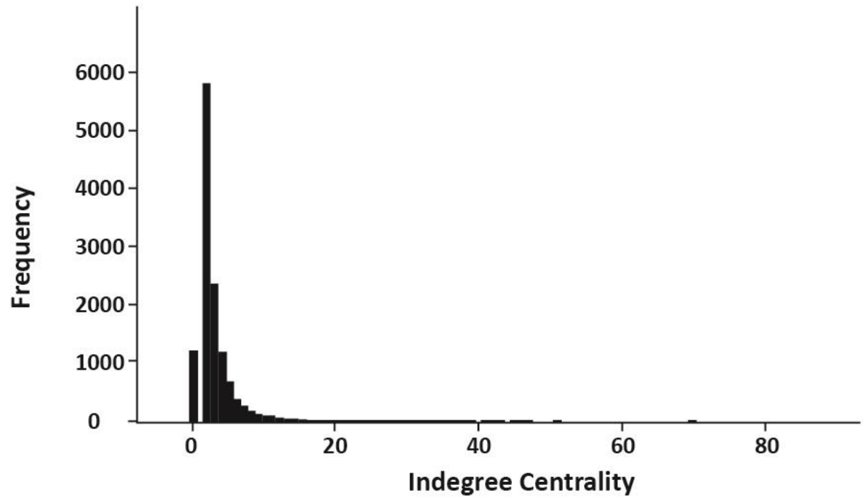


Figure 5.11. In-degree centrality distribution for all words.

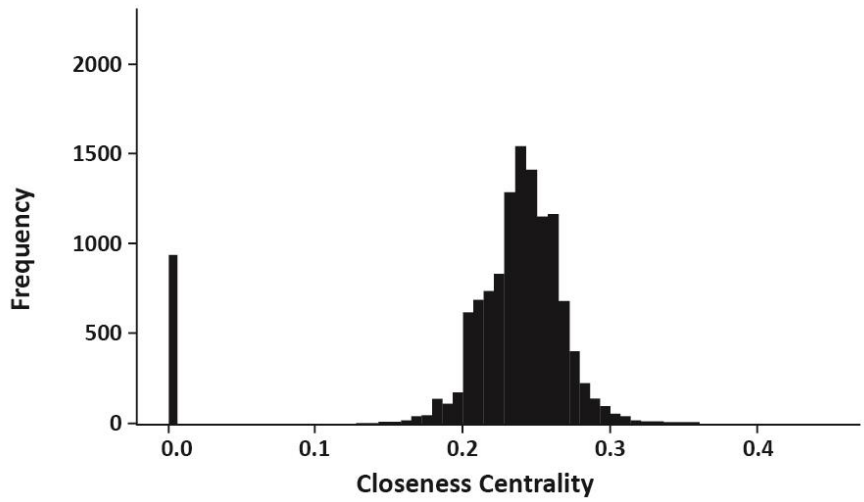


Figure 5.12. Closeness centrality distribution for all words.

The node in-degree centrality presents a long tail distribution with an asymptote in two edges, the minimum for contact nodes (Figure 5.11). A group of 1,217 nodes presents an in-degree score of zero. These nodes group original words that direct semantic relationships to other words but do not receive any. The in-degree centrality score of original words is lower with a mean of 2.56 edges against a mean of 3.32 edges in contact words. Differently, the nodes closeness centrality has a bell-shaped curve with its highest score near 0.2589 (Figure 5.12). Original words within the network show a mean closeness centrality of 0.1428 against 0.2392 of contact nodes. Thus, contact nodes possess on average a more central position than original ones. The image tags for each word confirm that 75.8% of the words in the network are related to all images. However, this distribution is different for original and contact nodes where 98.4% of original words are only related to a single image while 91.9% of contact nodes are related to all. Accordingly, around 2.0% of all words are exclusive to a certain complexity degree while 8.7% of them is exclusive to either symmetrical or asymmetrical architectures.

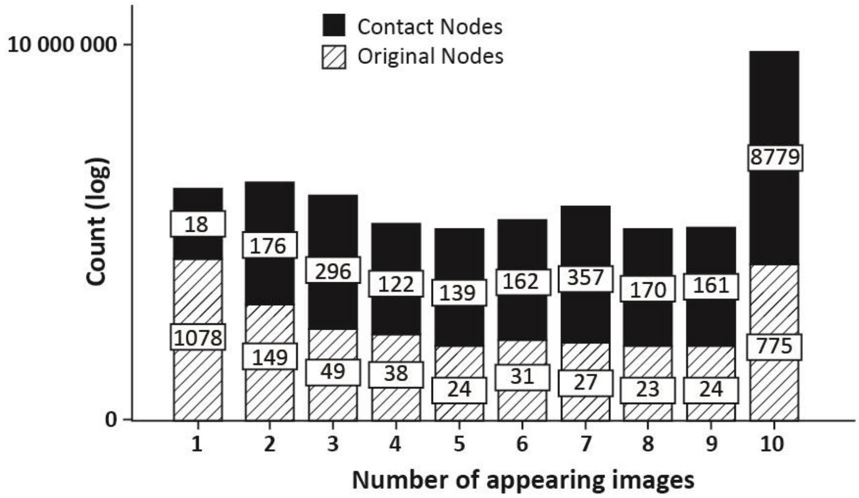


Figure 5.13. Total number of contact and original words related to a certain number of images 1-10.

The same algorithm used to find the semantic communities in the manual categorization modularized this network in 32 communities and 940 leaf nodes. These 32 modules gather between 0.78% and 5.86% of the network individually. A Chi-square test was used to test the fitness between the number of images related to each word and the semantic communities from the complete word network. The Pearson chi-square value shows that the semantic communities of the whole network have a strong effect with α values near zero. The distribution of the fitness shows a group of words that is concentrated in just one image and semantic community while there is another one connected across all images and all communities. Inside the original words pool, this division accounts for 1,058 words (47.70%) out of 2,218 are present in just one image and semantic community. In the other extreme 571 words (25.74%) are shared across all images and all modules. This indicates a core of words mainly composed by entailments that is related to all images surrounded by isolated clusters exclusive to particular images with specific themes.

	Original and Contact	Original	Contact	Shared all images	Exclusive to one image	Exclusive and in WordNet
Indegree centrality	3.1859	2.5613	3.3194	3.7466	0.0639	0.2703
Closeness centrality	0.2223	0.1428	0.2392	0.2459	0.0508	0.2150

Table 5.5. Closeness centrality across different word classifications.

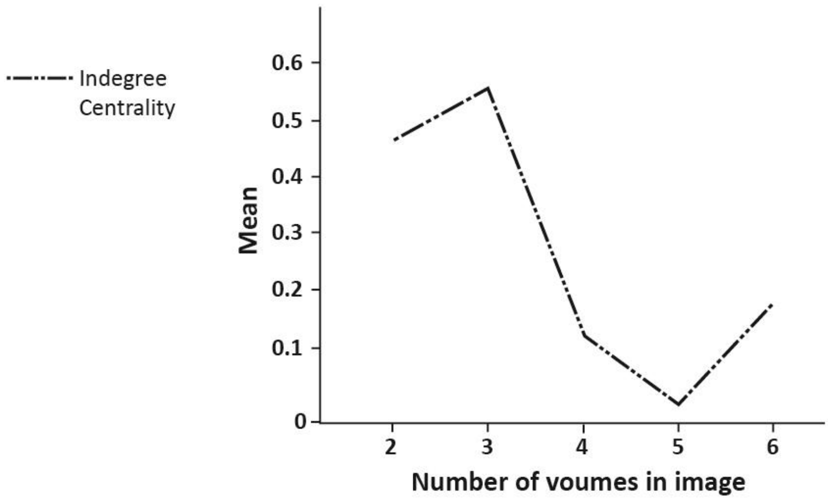


Figure 5.14. In-degree centrality for nodes within WordNet exclusive to a number of components (complexity degree).

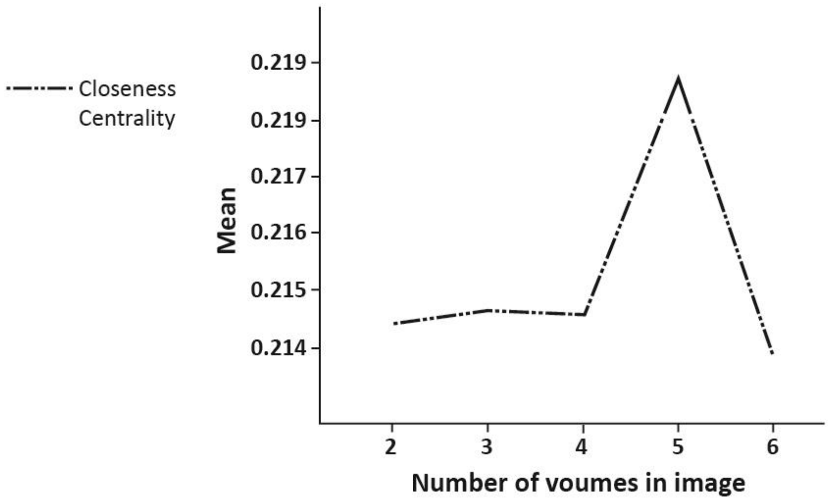


Figure 5.15. Closeness centrality for nodes within WordNet exclusive to a number of components (complexity degree).

The division between words that were present in all images and words that were exclusive for each of them created a second opportunity to verify the affordance of complexity over the structure of business opportunities. The analysis used the group of words exclusive to just one image as samples. 98.4% of the words that are exclusive to one image are original words leaving only 1.6% of contact nodes. Interestingly, 76.4% (n=837) of the original words are isolated words that were not found in the Wordnet structure. With these words included, centrality scores show a mean closeness score of 0.05 and 0.06 edges. Without them, closeness centrality rises to 0.2149 and In-degree centrality to 0.27 edges (Table 5.5). The remaining nodes that are properly registered in WordNet were used to test the centrality scores of in-degree and closeness centrality against each the number of components. In the same fashion as the evaluation within network scales, centrality scores do not show significant differences nor a trend that can be associated with the increment in complexity (Figure 5.14 and Figure 5.15).

5.6 Limits of the study.

The comparison between the breadth of semantic relatedness in human perception and a thesaurus structure has clear limitations. As shown above, 837 words were excluded by the algorithm since they were not included in the WordNet structure. When revised individually, these words describe categories such as brands, product names, user types, modifications of subcategory names, and compound labels frequently used in everyday language and media. This exemplifies the difficulty of incorporating evolving language in a formal thesaurus structure. Further recreations should consider the use of more fluid text corpora or the assembly of a special corpus.

Additionally, the selection of the evaluated concepts depends on manual interpretation of what can be considered a category. Whereas NLP relies on part-of-speech (POS) classification, some categories were generated from the interplay between different POS making them less compatible. In a similar way, natural language seems to interchange categories for broader superordinate categories in order to avoid redundancy. The selection criteria for this study used theories of product semantics. Yet, the incorporation of participants in the classification of the concepts could inform the generation of corpora.

The semantic manual categorization raised some themes that seem to match with interests of the oldest age group in the survey. Though, the background of participants was not considered since no specific reason was found in the theoretical background. Nevertheless, these matching concepts could be studied through an ethnographic study of the context with the participant entrepreneurs. Yet, considering the scores in all the statistical tests, improvements in the use of corpora may improve the understanding of the content of the semantic networks without showing different results for the correlation with complexity.

5.7 Study Summary

Study 2 analysed the semantic structure of results from entrepreneurial ideation in order to find possible effects of complexity in product architecture. Based on the results in Study 1, this study looked for the reduction of variables related to design expertise. The study presented a mental imagery exercise under an entrepreneurial scenario. The study showed a randomly generated image of varying complexity to participants and asked them to complete 13 entrepreneurial statements that describe the market opportunity. Data was parsed manually and with the help of an algorithm. Next, the algorithm searched lexical semantic entailments in the WordNet thesaurus and built a network representation of them. The algorithm measured the density of the network and the number of coinciding entailments between words mentioned in the same word pool.

Results from the analysis of this study show that there is no affordance of complexity present in the inter-relatedness of the vocabulary used in entrepreneurial ideation. However, the study shows that different entrepreneurial ideas shared contact concepts between them despite being generated in isolation. The analysis corroborated the presence of a shared nucleus of concepts across all images and contrasted it with the language that was not shared across different images. No effects of complexity were found amongst those words that were exclusive to particular images.

6 Discussion

This thesis presents two studies to inform the analysis of the creation of market opportunities with *Additive Manufacturing* (AM). The overall objective of the studies was to examine the effects of *complexity freedom* in the ideation of business opportunities. A review of the literature showed that an understanding of the creation of business opportunities as design exploration could leverage AM as a strategic resource for the design of firms. The data presented here consisted of two design exercises in the context of *entrepreneurial ideation* using stimuli of varying complexity. Study 1 consisted of a collaborative entrepreneurial ideation exercise facilitated through a building kit. The exercise simulated conditions of traditional fabrication and AM. The complexity and afforded interactions of the resulting product designs were analysed. In Study 2, an entrepreneurial ideation exercise was carried out using images of abstract geometries of varying complexity. Participants interpreted these images to generate business ideas. The complexity of the semantic networks in the answers was compared amongst the ideas produced by participants.

6.1 Summary of Key Findings

The findings from both studies do not support the hypothesis that that the main feature of AM, complexity freedom, plays a major role in entrepreneurial ideation. Study 1 focused on complexity freedom as a feature of the technological means that could afford more complex product architectures. In study 1, the presence of complexity freedom in the experimental groups showed a significant increase in the total material elements used in the final solution. This difference was significant in both the number of elements used and their size. However, the interdependencies between the individual components and thus the final architecture of the solution shows no difference between experimental and control groups. The analysis of the afforded interactions of each solution shows that the mechanics of each component do not increase the degree of involvement of the user with the presence of complexity freedom.

Study 1 showed that the expenses of teams with simulated AM restricted their production as shown in previous studies (Allen, 2006; Atzeni & Salmi, 2012; Baumers et al., 2016). This study also revealed that entrepreneurial ideation is restricted by the fabrication of a central component of high complexity. Production is restricted despite having complexity freedom for the redistribution of connections amongst all other components across team members. The qualitative analysis of the ideas generated in study 1 shows a set of basic concepts that were generated by multiple teams. The architecture of these concepts does not present a pattern that can be traced back to functional allocation. Overall, study 1 clearly suggests that complexity freedom need not afford the ideation of more complex product architectures that can mirror more complex business opportunities. The exploration of the ideation means by the participants does not seem to prioritize the allocation of functions in the architecture as inferred by the models of product architecture mirroring (Colfer & Baldwin, 2016; Conway, 1968). It is thus impossible to support the idea that complexity freedom is an important factor in entrepreneurial ideation based on the results of Study 1.

Study 2 compared the complexity of the semantic networks from a mental imagery exercise. The results suggest that the semantic structure of entrepreneurial ideation need not be affected by complexity in the ideation stimuli. The networks of semantic entailments of the ideas generated by participants in study 2 do not show significant structural differences in relation to the complexity of the input images. Yet, an analysis of the categories mentioned in all answers together indicates that nodes that represent semantic connections between concepts increased even as the networks accumulate and their density decreases. A detailed analysis of this complete set of words shows a core of semantic entailments shared by images. Such core was “surrounded” by concepts that are exclusive to particular shapes. A majority (75.83%) of all words in the complete network was connected semantically across images. However, this number varies drastically for words written by participants (1.6%) and the semantic entailments of such words (91.9%). Therefore, participant responses share common lexical semantic entailments, which indicates a shared semantic domain. An analysis across the words that were exclusive to each image shows no effect of complexity in the structure of the semantic networks generated through entrepreneurial ideation. Hence, there is no clear evidence to support the hypothesis that increased complexity in means is mirrored in the complexity of creative results.

6.2 Discussion of Results

Both studies suggest that the exploration of stimuli in entrepreneurial ideation does not prioritize the allocation of functions naturally as inferred by the models of architecture mirroring (Colfer & Baldwin, 2016; Conway, 1968). This thesis thus suggests that as a key consequence for the use of AM technologies, the benefits of complexity freedom need not affect entrepreneurial ideation.

Study 1 showed teams that focused on the selection of the functional principle of the idea. This artefact functionality recalls the *operational principle* as described by Murmann & Frenken (2006). This operational principle consists of the knowledge that is needed to create a solution within a technological category. This is shown when participants describe their own results under existing artefact categories such as “slider”, “launcher”, “kart”, or “catapult”. Named categories indicate a functionality principle despite having architectures that were different from the archetypical solution of each category.

In Study 2, the results of entrepreneurial ideation form clusters characterized for its semantic content rather than complexity. After discarding complexity and symmetry, the shared language across all images seems to correspond to the morphology of the images. This thesis suggests that entrepreneurs recognize the typicality of the morphology of images instead of the functional structure of their form. Namely, semantic clusters that describe common entailments of categories and identities are found instead of new interpretations of available volumes in the image. The main contribution of this thesis is, thus, that entrepreneurial ideation may be strongly shaped by the morphology of the stimuli for ideation conformed by the means at hand of the entrepreneur.

Morphology is not a concept explicitly present in the literature on the creation of markets and industries. Ulrich (1995) describes the effects of different types of product architectures including integral and modular configurations. Product architectures are divided in integral, slot, bus, and sectional types according to the style of the component coupling. This typology of product architectures has direct consequences in product variation, flexibility and both for product and organizational performance. While the analysis of such architectures focused on the systemic descriptions, these typologies address morphological criteria. Based on our studies, this thesis argues that exploration of the coupling structure works at a morphological level instead of a system one. However, the implications of the morphological consequences of these choices disappears from product architecture literature. Instead, the field has focused on a systemic understanding of the relationships between functions and components. This is particularly evident in the techniques and tools used in the analysis of dominant designs (Browning, 2001; Ulrich, 2016).

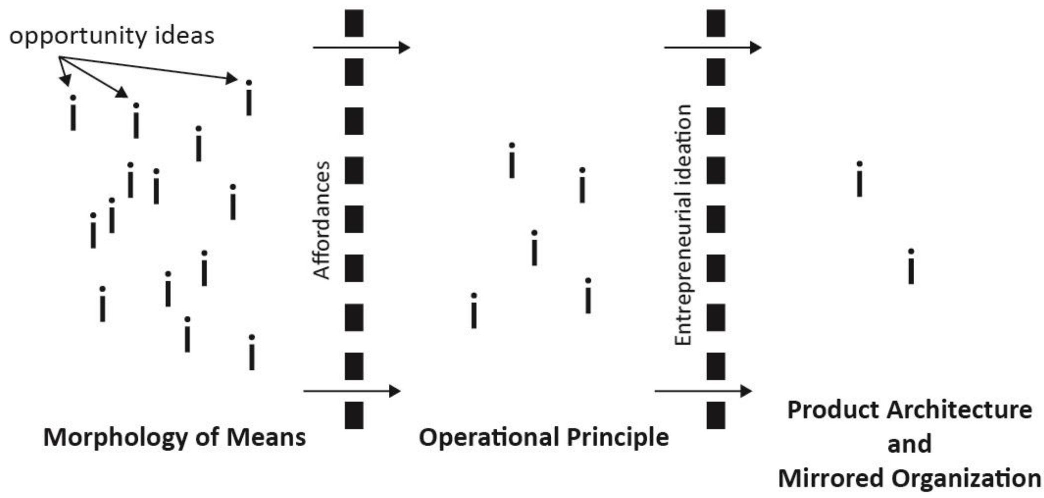


Figure 6.1. Evolution of the design space of business opportunities.

Murmann & Frenken (2006) argue that the definition of an operational principle is central to differentiate between technologies, for this principle dictates the interaction between components in a design. Operational principles are defined as the articulation of practical knowledge for the successful performance of an activity (Polanyi, 2012). It is argued that operational principles make intelligible the properties of materials, tools, and processes that are found suitable for the successful accomplishment of the desired activity. Hence, operational principles are intrinsically related to the morphology of the elements that constitute a technology. Murmann & Frenken (2006) suggest that the operational principle defines the key technical dimensions that exist in a product category. Therefore, the design space for a product architecture is filtered by the morphology of materials, tools, and processes (Figure 6.1). Thus, this thesis concludes that idea exploration in entrepreneurial ideation may be heavily influenced by the morphological traits of a design.

It is possible to expand this argument to theorize that the structures perceived by participants in both studies correspond to the operational principles provided by the affordances present in the morphology of the material provided. The results of Study 2 could be explained by the hypothesis that common categories of solutions were generated by participants due to the same affordances of the morphology of the stimuli used as building set. It is possible that the categories used to name ideas in Study 1 and to interpret shapes in Study 2, correspond to the typical categories that they identify from the affordances in the morphology of the explored stimuli via embodied perception (Aziz-Zadeh & Damasio, 2008; Smith & Gasser, 2005). In relation to AM technologies in entrepreneurship, the studies presented in this thesis suggest a need to research the role of morphology. Therefore, the flexibility proposed by supporters of

AM technologies needs to consider the role of morphology instead of assuming that freedom of complexity bypasses the limitations of traditional manufacturing.

Additionally, these studies also indicate a need to study entrepreneurship as design exploration that is identified and supported by methods for the study of product morphology (Krippendorff, 2006). In the study of market creation as proposed by Sarasvathy and Dew (2005), entrepreneurship research can integrate morphology as a fourth point in the account of means attainable by the entrepreneur. In addition to “Who I am? Whom I know? What I know?” the data presented in this thesis would suggest “What do I perceive?” to reflect upon the affordances of the means at hand. This mechanism of perception of affordances and the elicitation of metaphors, is a process shared with other stakeholders that up until now is part of the trial and error in prototyping. Making explicit the effects of morphology complements current understanding of entrepreneurial ideation by using the perceptual features of afforded entailments as generative arguments in the negotiation of effectual contracts between partners.

An account of morphology for the design of a firm instead of only a business model, requires also the development of a hypothesis that recognizes perceptual processes and connects them to the existing strategy frameworks. Based on the results of this study this project implies that a base for this concept exists in the concepts of value network (C. M. Christensen & Rosenbloom, 1995). A further study of morphology in entrepreneurial ideation should map the existing accounts of value network structures, to the morphology of the products as they evolved together. However, the insights drawn from the exploration of the semantic entailments of entrepreneurial ideation can give an initial insight to this relationship between morphology, the value network, and existing strategy frameworks.

Relationships between morphology, firms, and strategy.

The articulation of morphology in with the purpose of designing a firm also requires a reinterpretation of the theories of the firm. A reinterpretation would portrait it as an object of design that is interpreted by the user and enacted through affordances just as any other human made artefact (Dong et al., 2017; Jelinek et al., 2008). In context of entrepreneurship studies, this enactment of the firm morphology involves an interplay with strategy. This interplay requires the delineation of boundaries between the artefact itself and the set of activities that happen around it which are orchestrated through strategy. Existing arguments do not make a clear difference between the inner and outer boundaries of the firm artefact and consequently, fail to prescribe the behaviour of the artefact users outside strategy. Thus, the study of entrepreneurship cannot address causal relationships between the semantics of the firm created in entrepreneurial ideation and the strategy itself. Yet, a critical assessment of the behaviours of stakeholders in firms shows that more behaviours are affordable to users beyond those recognized by economics and strategy (Munn, 2017).

The theories that describe mirroring effects do not account properly for the shape of the initial solution space and imply that functional allocation is developed in the abstract, defining the design space to a functional level (Esparza et al., 2017). A functional definition of artefacts, such as the one in these models, leaves no space for the consideration of the possible effects of affordances. In a systemic view of artefacts, functions are a desired output of a designed system. Contrary, affordances are not results of the artefact, neither do they reside in it, but represent relationships between an agent and an artefact (Chemero, 2000, 2003). Existing attempts for creating affordance-oriented design processes feature processes that focus in possible desired and undesired affordances between agents and systems before component allocation (Maier & Fadel, 2009). Though, these methods do not address the design process as an exploration and thus, do not recognize the evolution of the problem space where morphology has a strong influence. The results from our studies suggest that the stimuli used in ideation present affordance structures in their morphology that already influence the conceptualization process of firm and strategy from the beginning.

The influence of morphology indicates that manufacturing means, may also communicate a spectrum of meaningful geometries and uses that are affordable through them. Such meanings relate to the abilities of the entrepreneur and therefore are different from DFM requirements that focus on functional descriptions of manufacturing processes. Therefore, the influence of manufacturing processes in entrepreneurial ideation could be considered as part of the semantic processing in the firm effectuation process proposed by Sarasvathy (2004). This priming process may always have been present in the creation of manufacturing industries. However, the appearance of digital manufacturing has condensed the system of artefacts that traditionally constitute complex manufacturing processes into a simpler configuration. Digital manufacturing manages to bypass many of the artefacts inherited by subtractive manufacturing with the use of CAD and CNC tools. Consequently, semantic entailments tied to artefacts and stakeholders that evolved into the slow and complex processes used in subtractive methods are not implicated in digital manufacturing. Particularly the use of AM reduces the perceived affordances of the means to the extreme case where most of the artefacts involved in the manufacturing process are substituted by a digitally controlled deposition process. For this reason, the creation of businesses with AM is missing a context that frames affordable structures for entrepreneurial ideation. Hence, as supported by our results, it is difficult to model a process of entrepreneurial ideation in the abstract.

6.2.2 Research questions review.

Q1. How does complexity freedom impact early entrepreneurial ideation?

Whilst the research questions supposed that complexity would afford more complex results through entrepreneurial ideation, the studies presented here do not support that functional allocation is a priority in the ideation of market opportunities. Moreover, the results revealed a more important role of morphology in the conceptualization of the market opportunity.

Q1a. How does complexity freedom affect product architecture in entrepreneurial ideation?

There is no evidence in our studies to support an effect of complexity freedom in the creation of more complex product architectures. Likewise, there is no evidence that supports that the ideated product architectures afford more and more complex functions.

Q1b. How does complexity freedom affect the structures of ideated firms?

There is no evidence in our studies to support an effect of the implementation of complexity freedom in the ideation of business opportunities. Yet, AM still has the flexibility to integrate or transform the morphology of the design means by imitating affordances that result from different manufacturing despite having restricted morphological influence itself. The flexibility of AM can give the entrepreneur access to the creation of morphologies that leverage this flexibility and go beyond the mirroring of the initial product architecture. AM has the potential to combine the boundaries that separate technological categories (and industries). Firm design with AM can take a step back in existing categories that correspond to other manufacturing processes and introduce the design of new products by combining semantic affordances from radically different sectors.

However, the challenge that faces firm design with AM resides in the articulation of the entrepreneurial ideation process. An effective firm design process supported by AM would depend on tools that enable discussions at a semantic level that considers the affordances of the rest of the means accessible to the entrepreneur. The focus of firm design moves away from the orchestration of the product and organizational architecture and focuses on the understanding of the entrepreneur's/stakeholder's abilities and the relationship they have with the surrounding environment. Firm design with AM needs methods that extracts these affordances as design requirements in order to discuss venturing at the level of afforded operational principles. The development of tools that manifest the possible scenarios and simulate the semantic entailments that shape transactions in each scenario are clearly different ones from the discussion found today in AM research.

6.3 Implications of This Study

6.3.1 What does it mean to study firm creation as design?

The articulation of the methods in this thesis shows similar and contrasting points between the fields of entrepreneurship and design. This thesis shows the closeness that design has to the ontological questions in the creation of ventures originally studied from an economic perspective. The definition of design has a strong relationship with the intersection of the two areas where Davidsson (2016) situates entrepreneurship: the micro level of novelty introduction, and the creation of small organizations. In this design context, Sarasvathy's arguments can be understood as a proposal to situate the process of novelty introduction in the field of design. Similarly, they are also an invitation to consider the firm as an artefact inside the independent organization.

Traditional views of entrepreneurship have a naturalist perspective where market opportunities pre-exist and need to be searched. Arend et al. (2015) accuse effectuation of unjustified optimism when proposing that entrepreneurs can traverse different types of firms contingently because they do not account for the nature of exogenous opportunities. Nevertheless, the effects of morphology in entrepreneurial ideation evidence how these opportunities are afforded through contingency to entrepreneurs. This project postulates an agential realist ontology as an alternative to the naturalist views of entrepreneurship that can support the conception of the opportunity as the result of a continuous exploration of the entrepreneurial context. Agential realism changes the unit of study from objects to phenomena. Phenomena are co-created by agents that belong to a system as is the case of the market opportunity created from the affordances that emerge from the means and the entrepreneur's capabilities.

The object of study and firm design

Sarasvathy (2004) stresses the need to make a focus shift in order to study the nature of firm artefacts (successful and unsuccessful) instead of the contradicting nature of entrepreneurs and unpredictable opportunities. A firm artefact rooted in semantics separates the structure and behaviours that surround the firm and creates a model to fit existing definitions of organizations and management. At the same time, it describes the firm artefact as a result of an exploration creative process. Results from this study support this view and show the analogies between ideation in firm design and ideation in other design processes supported by the manipulation of artefact semantics. Consequently, firm design opens up to the study of the creative cognition in the context of entrepreneurship as suggested by Dimov (2007).

The study of firm design can provide a broader understanding of the relationships of artefacts and the cultural environments and practices that surround them. The study of a firm artefact also introduces the concept of affordance to the study of entrepreneurship. As discussed in this study, affordances can be understood as the relationships that show available behaviours that an entrepreneur can effectuate with the resources at hand. The morphology of the means at hand includes manufacturing technologies as much as products and influences the output of entrepreneurial ideation. The discussion of affordances, functions, and architectures needs further development to create actionable frameworks of firm design and opportunity creation.

Practice of entrepreneurship

Within entrepreneurship practice, design already has a relevant role in the creation of ventures. Mainly built based on the Stanford view of design thinking, current methods of design in entrepreneurship imply indirectly the role of exploration in the design process (Brown, 2008; Martin, 2009). The incorporation of such methods still propose a simplified design process centred exclusively in the figure of the designer that does not recognize the plurality of other stakeholders as designers (Ideo, 2019; InVision, 2019; Kimbell, 2011). The results of Study 2 show how the operationalization of theories related to cognition, semantic manipulation, and ideation can inform the practice of design and connect it to a more plural population of stakeholders in that design of business ventures. Accordingly, a revision of the methods used in this thesis can also be used to develop tools for the study of the form and entailments of firms as artefacts. These and other design methods can be connected to the current frameworks and tools to open their scope and articulate more entrepreneurial affordances of the firm.

6.4 Study Limitations

The study was limited by the restrictions in time and resources to iterate and direct the focus of the investigation. From a theoretical perspective, this project fails to draw the precise boundaries of ideation and design in opportunity creation. As a cross-disciplinary project the lack of final boundaries raises questions about the articulation between disciplines. Particularly, the resource restrictions of this project limited the exploration of other philosophical and methodological articulations of design tools such as the manifestation of the market opportunity and the potential of strategy canvases.

Considering the aim of the study, the iteration of methods gave also the opportunity to focus in the operationalization of complexity freedom and its technological context. The limitations of the design of the building kit, the structure of the thesaurus, and the design of the image generation algorithm are issues that need further development. The lack of specificity in the design and management literacy of entrepreneurs forced trade-offs in the design of the tools with the purpose of presenting versions of AM that were understandable enough. These limitations were evident in Study 1 where participants were not able to manipulate CAD software. Differently, in Study 2 the limitations of management literacy restricted the design of survey items that could be more specific and draw categories that belong to specific stages of the value chain. The re-implementation of the methods could refine the documentation and definition of variables to provide more insight into the participant's interpretation of affordances. The structure of the methods used may serve as an initial step for the refinement of methods that study creativity with technology in entrepreneurship. Next a critical review of the research process from the perspective of the researcher is presented.

Researcher as designer.

The main motivation for the study of the relationship between AM and business creation came from professional practice. Thus, the integration of the research methodology represents an important output of this research project. The experience of the researcher as a professional designer includes the collaboration with incubators and entrepreneurship programmes, in addition to the management of an own business. Under a scientific lens, the practice with workshop material production for strategic design and the collaboration with stakeholders, synthesized with the theoretical background in order to generate sound methods. In the same fashion, it eased the interaction with stakeholders and participants. Some examples of such were the translation of concepts and prototyping of methods and the operationalization of complexity freedom. As mentioned above, experimental studies in entrepreneurship are still an area under development and it is the objective of the thesis that the contribution of design methods of research and practice will help in its development. Within the research team, a designerly stance contributed to the creation of the measurement means by treating the method as an exploration in the same way as the process that is object of this study.

Reflecting from the practice of research, this project situated the author within the design domain. Particularly, the understanding of the relationship between the creative processes that constitute the designer practice and the macro levels of strategy and technology change. Popular views of entrepreneurship and innovation are created from naturalist perspectives of industrial change to suggest that industries are disrupted inevitably in one and only performance dimension. Accordingly, businesses need to innovate in order to survive. The methods and results of this thesis set in perspective these claims and question assumptions such as the scope of innovations, the role of morphology and semantics in the creation of performance dimensions, and the agency of entrepreneurs as designers. Defining an agential realist epistemology, this project has also contributed to the awareness of connections that leverage individual actions and effectuate scalable change. Additionally, this project has helped the researcher to sketch a personal stance towards the design domain. The thesis explores design in two different levels: one of design as a science, and one of design processes and contexts (Galle, 2018). As part of the research apparatus, the author considers that the practice and theory of design and entrepreneurship have fruitful articulations yet to develop.

6.5 Agenda for Further Research: A Proposal for the Study of Morphology in Entrepreneurial Ideation

The presented studies in this thesis explored the interaction of entrepreneurs and products in order to track how complexity affects entrepreneurial ideation of business opportunities. Consequently, the conclusions that bring up the role of morphology before the development of product architecture were not the focus from the beginning of the study. The unexpected nature of these results bump onto the limits of the selected methods that cannot account for the complete role of morphology in entrepreneurial ideation. These methods should be explored further in order to study the effects of morphology more thoroughly.

WordNet was built as a lexical database of the English language for the study of linguistics and the development of Natural Language Processing (NLP) tools. Its structure resembles the structure of a dictionary where possible meanings of words are listed and ranked after been selected by expert linguists. A database for the study of the study of morphology needs to go beyond the lexical and syntactic structures of spoken language in order to accommodate other semantic relationships that stem from visual language perception like metaphors, metonyms, complementary, and substitute objects (Krippendorff, 2006).

In a similar way, there is a need to re-order the meaning of semantic entailments that is not based in NLP disambiguation techniques and contextualizes visual language. Methods for disambiguation rely on the measurement of meaning vectors or semantic relatedness (Bird et al., 2009b; Budanitsky & Hirst, 2006; Krippendorff, 2006). The inclusion of visual language would need to monitor these vectors for images and shapes with the aid of users. The proposed modifications look for the adaptation of spoken and visual language in the context that surrounds the use of the artefact. The challenge for these methods is the dynamism of language evolution and the determination of a level of semantic analysis that balances the precision of meaning definition with the breakdown of visual compositions. Three directions for the future refinement of the methods are proposed: the development of focused corpora, the development of alternative algorithms for measurement, and the experimentation with morphologies that correspond to different DFM guidelines.

Business oriented corpora.

An alternative to the use of thesauri is the generation of specialized corpora for the visualization of morphological entailments within a business venture. A specialized semantic corpus has the purpose of drawing only the relevant semantic entailments that are relevant to the interpretation of morphology. Hence, meanings that can be drawn in other contexts might not be considered. Business documentation related to the product categories represented by the morphology constitutes a rich background for the capture of entailments. Semantic corpora can be drawn from documents such as contracts, invoices, and strategic communication manuals. In the same way as Study 2, words can be classified according to their role as part of speech or categories. Words can be linked semantically by appearing in a same document or coming from the same source. Visual references that include logos, ads, guideline manuals can be included. Including invoicing can also provide evidence that links product categories to capital movement across the firm. Whereas this thesis may not portrait a theory of successful firm artefacts, the correlation with transactions can help in the description of affordable contracts even in a financial dimension.

Strategic documentation can also help the study of the effects of morphology. Corporate documentation is rich and describes strategy in different degrees of specificity according to the public it must address inside the corporation. Thus, the creation of a semantic corpus based on strategic documentation would also give a view of the specificity of the references at different levels of a corporation. Additionally, platforms that provide companies with social media profiles can provide an image of the language used to refer the product category in digital brand touchpoints. The raw data used for this kind of corpora can also provide an immediate image supplied also with the development of new idioms, the articulation with visual language such as images or video, and the use of hashtags.

Operationalization of semantic relationships.

The design of semantic databases can also benefit from the operationalization of specific semantic relationships that are not related to the lexicon. Semantic relationships that concern ideation processes must be defined by the role they have in associative thinking. It has been proposed that during the incubation stage of the creative process problem structure loses resolution (Jankowska & Karwowski, 2015). As proposed by the Geneplore model, the lack of detail seems to highlight structures in the problem that are associated with others stored in memory (Finke, 1996). Such psychological associations transfer properties in the shape of inferences that take the shape of analogies, metaphors and metonyms that are transferred from one object to another. Therefore, the operationalization of these psychological inferences can provide semantic databases with a structure that is more suited to describe creative incubation. Algorithms that work based on probability are used in NLP as a substitute to meaning determination (Hardeniya et al., 2016; Thanaki, 2017). Contrary to the evaluation of possible meanings, a machine learning algorithm can predict the probability of finding semantic relationships between two features.

Evaluation of different DFM approaches to morphology.

The morphology of the construction kit for Study 1 and the stimuli for imagery in Study 2 were designed separately to show differences in the complexity of product architecture. Hence, there is no ground to compare the morphology of both sets. Methods that objectively compare two different morphologies may be based on similar studies that compare AM with other manufacturing processes (Allen, 2006; Faludi et al., 2015; Khajavi et al., 2014). As described by Lu & Suh (2009),the acquired complexity determines the final configuration of the architecture and is the result of solving functional requirements with a limited manufacturing process. Hence, the comparison of the morphology of two manufacturing processes can be used to evidence differences in the semantic entailments of entrepreneurial ideation since they can present the same functional requirements.

Study 2 showed an opportunity to develop artefacts for research that are different to existing products and could project biased metaphors. The study of morphology in entrepreneurial ideation can deliver images similar to the ones used in Study 2. Yet, it can also allow the study of manufactured geometries that entrepreneurs could manipulate. The study of embodied cognition suggests that the use of artefacts is embedded through use and can be recalled through language (Aziz-Zadeh et al., 2006; Aziz-Zadeh & Damasio, 2008). Morphologies with different affordances may elicit different business opportunities despite having the same product architecture.

6.6 Chapter Summary

The studies presented in this thesis show no evidence of the influence of complexity freedom in entrepreneurial ideation. This chapter suggests that studies of entrepreneurial ideation need to focus on morphology of the stimuli for ideation. Morphological analysis could be used to study product architecture and its *mirroring process* in firm creation. The influence of morphology is also addressed in the context of AM suggesting that a hurdle for the development of entrepreneurial ideas using AM is the lack of semantic influence around the manufacturing means. Thus, the use of AM for entrepreneurship could be accompanied in the future by a survey of semantic entailments that supports ideation and AM can also be used to mimic or merge morphological traits usually accessible through other manufacturing processes. The research questions were revisited under the view of this discussion.

The chapter addresses the limitations of the study and a critical reflection from the researcher's point of view. Finally, a research agenda is proposed addressing the documentation and representation of semantic entailments.

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AM exploration exercises

This appendix presents a summary of five exercises used to explore the use of AM technologies and the claims of different frameworks of DFAM.

I. Neighbours (Material affordances, complexity and customization)

Complexity freedom gives the entrepreneur/designer the opportunity to incorporate more functional requirements to the design process. The first implemented exercise considered the incorporation of data as a functional requirement of the designed product. The final product incorporated data to shape the form of a doll that represented specific statistics of neighbourhoods in Auckland, NZ. The dolls are proposed as tools for introducing the relationship of community openness and cooperation. The neighbour doll used the material affordances as proposed by Hague et al. (2004) to customize a product that could be produced in large batches using AM.

Data is one of the most important resources for decision making in our economy today. What powers this data is the ability business and technology have developed to leverage it to infer behaviours of users (Davenport et al., 2012). However, its accessibility is restricted to large corporations and governments (Weigend, 2017). Against this, data physicalisation leverages the perceptual exploration skills of the user, facilitates engagement, and makes data more accessible to the differently-abled and the general public (Jansen et al., 2015). Data objects are a particular variant of data physicalisation. An object is considered a data object if it has been configured to encode data in its form and function (R. Sosa et al., 2018). Data objects exploit the existing references in everyday objects in action to draw data near to users. They also represent a new opportunity for product design to contribute to the critical engagement with the ever-growing amount of data.

The current project was part of a “data to object” exercise implemented along with first year students of the Bachelor of Creative Technologies at COLAB. The objective of the exercise was to physicalize data present in the time use survey datasets from the office of national statistics in New Zealand website, Stats NZ (Statistics NZ, 2018). The result of this data physicalisation exercise was entitled “Neigbours”. Inside the time use survey from 2009/2010, data was available for the time New Zealanders allocate to different groups of people (family, alone, other known people, unknown people, and other family). The time allocated to unknown people by neighbourhood was selected as a proxy for openness. The goal was to design a system that showed metaphorically how openness shapes the possibilities of cooperation.

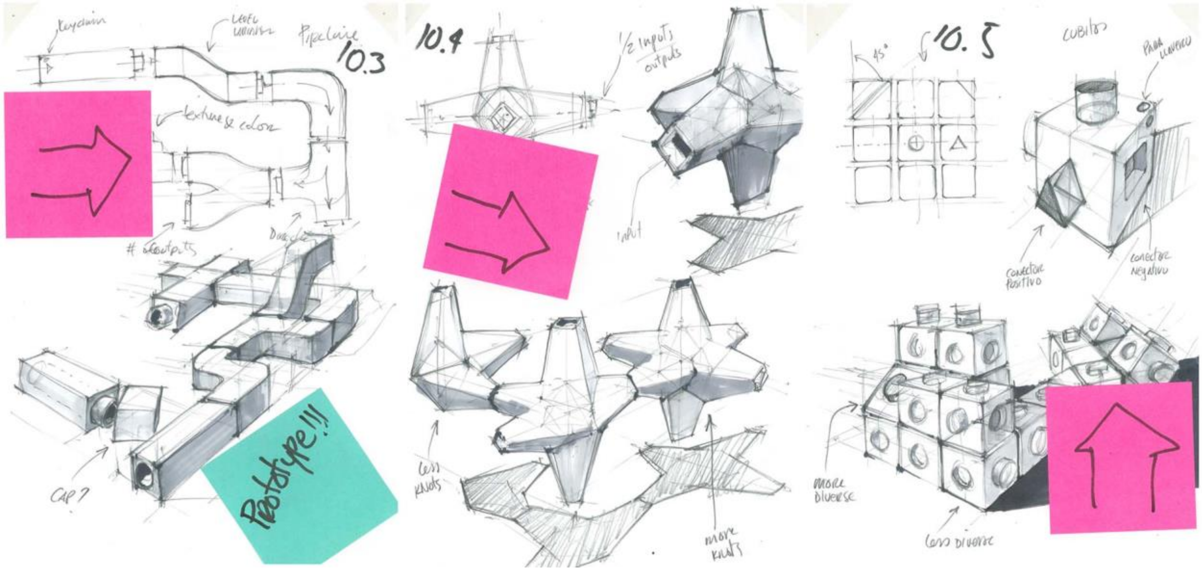

Figure 0.1. Complexity freedom permitted the exploration of very diverse configurations and metaphors.

A FDM Makerbot printer was used to experiment with designs that could exploit the flexibility of polyactide plastic (PLA) in diverse connection configurations. At the same time, familiar metaphors of connection and cooperation present in children's objects were explored (Figure 0.1). The final version of the Neighbour figure resembles a toy with a humanlike shape. The Neighbour's arms and legs intercept in the middle of the body making an "X" configuration. The arms and legs are conformed by four parallel bands of 0.4 mm PLA in the shape of a sinusoid curve with a clamp or a cylinder in the end that symbolize hands and feet. Feet fit in hands in order to assemble networks of Neighbours. According to the data by neighbourhood, the amplitude and wavelength of the bands change therefore making them more or less flexible. The amount of time allocated to unknown others was normalized to a score from 0 to 10. In the middle of the toy, the score appears in the back while a happy face appears in the front. Each Neighbour is intended as a building block for children to print in Fabrication Laboratories (FABLABs) using the same algorithm. Altogether, children from different neighbourhoods can try to assemble geometries with others who have different flexibility.

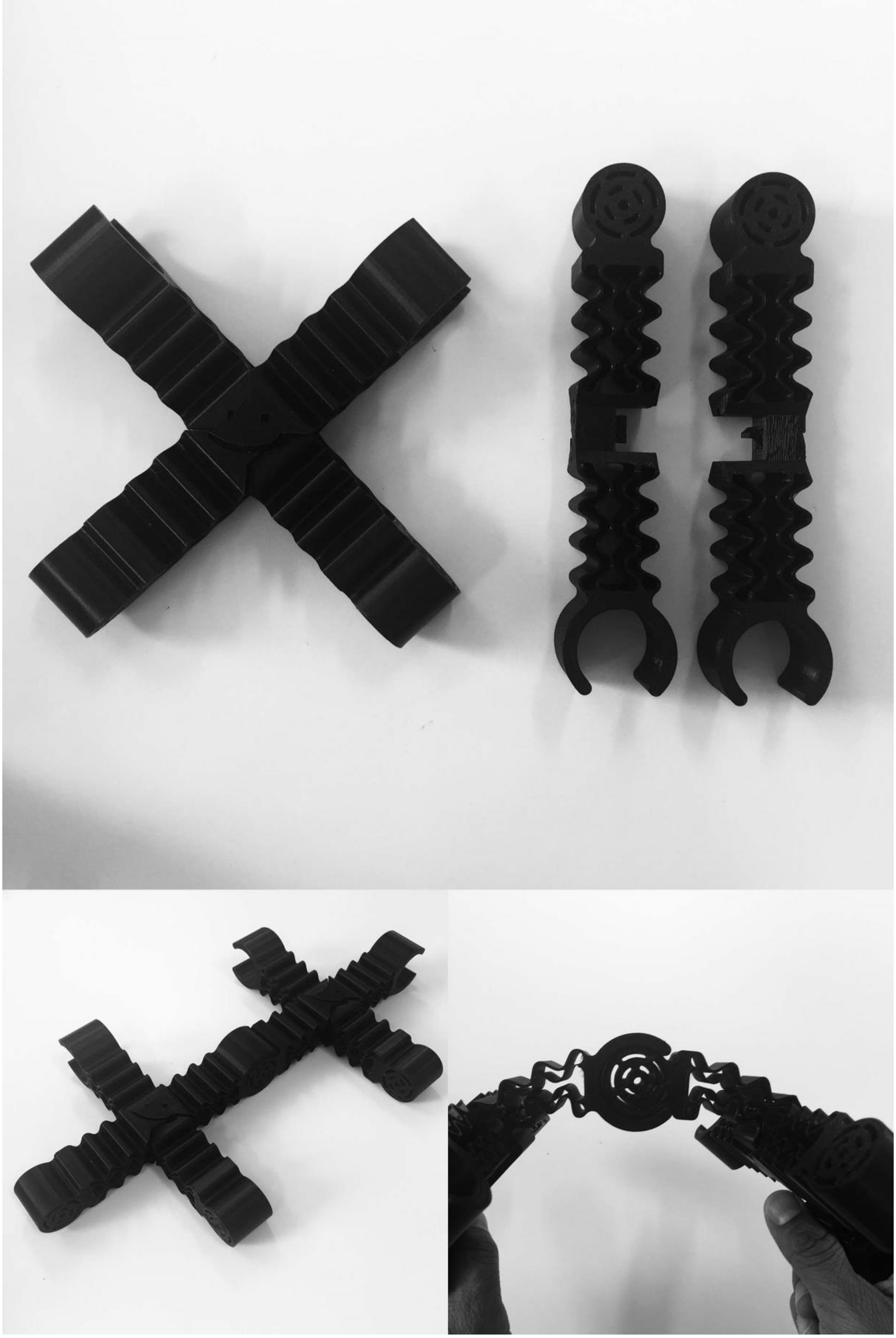

Figure 0.2. Neighbours final configuration, assemblage, and demonstration of flexibility.

The 3D printer fabricates the Neighbour in two sets of arm-leg that assemble in the middle. It implements the recommendations of DFAM by reducing the angles where the printing head must use support material and aligning the structural stress with the layer direction. At the same time, it optimizes the space and material needed by the printer reducing the amount of time needed to print each toy from four hours when printed altogether, to less than two hours. The Neighbour was designed in Rhino 5.0 software with the aid of the Grasshopper plugin for parametric design. The process required the abstraction of the shape into programmable operations. This generative algorithm structured the mapping of the statistics values to the properties of the sinusoidal curve and supported the creation of sets according to particular neighbourhoods and their scores. Neighbours exploited the material properties in FDM, the possibilities of DFAM, parametric modelling software, and the available customization.

II. Parametric Tripod furniture (Generative algorithms)

Design is the core capability leveraged by AM. The evolution of design tools in the last 25 years has developed the ability to incorporate system dynamics in concept analysis and synthesis along the design process. Particularly, design synthesis tools have affected the role of the designer shifting concerns from objects to system interactions, components, and processes (McCormack et al., 2004). One of the strategies proposed to leverage design through AM is the use of generative algorithms for the creation of meta-projects. The objective of generative design is similar to the concept of evolution of fitness in nature, where the combination of elements (such as proteins) is synthesised and proved in the environment. This project uses generative design to produce particular instantiations of itself as a product for a business venture. As a product, a meta-project provides an adaptable solution that users in different circumstances can modify before fabrication. Hence, by designing an algorithm, the entrepreneur/ designer designs multiple solutions. The parametric tripod is designed with a generative algorithm that adapts the furniture size to the available space and material.

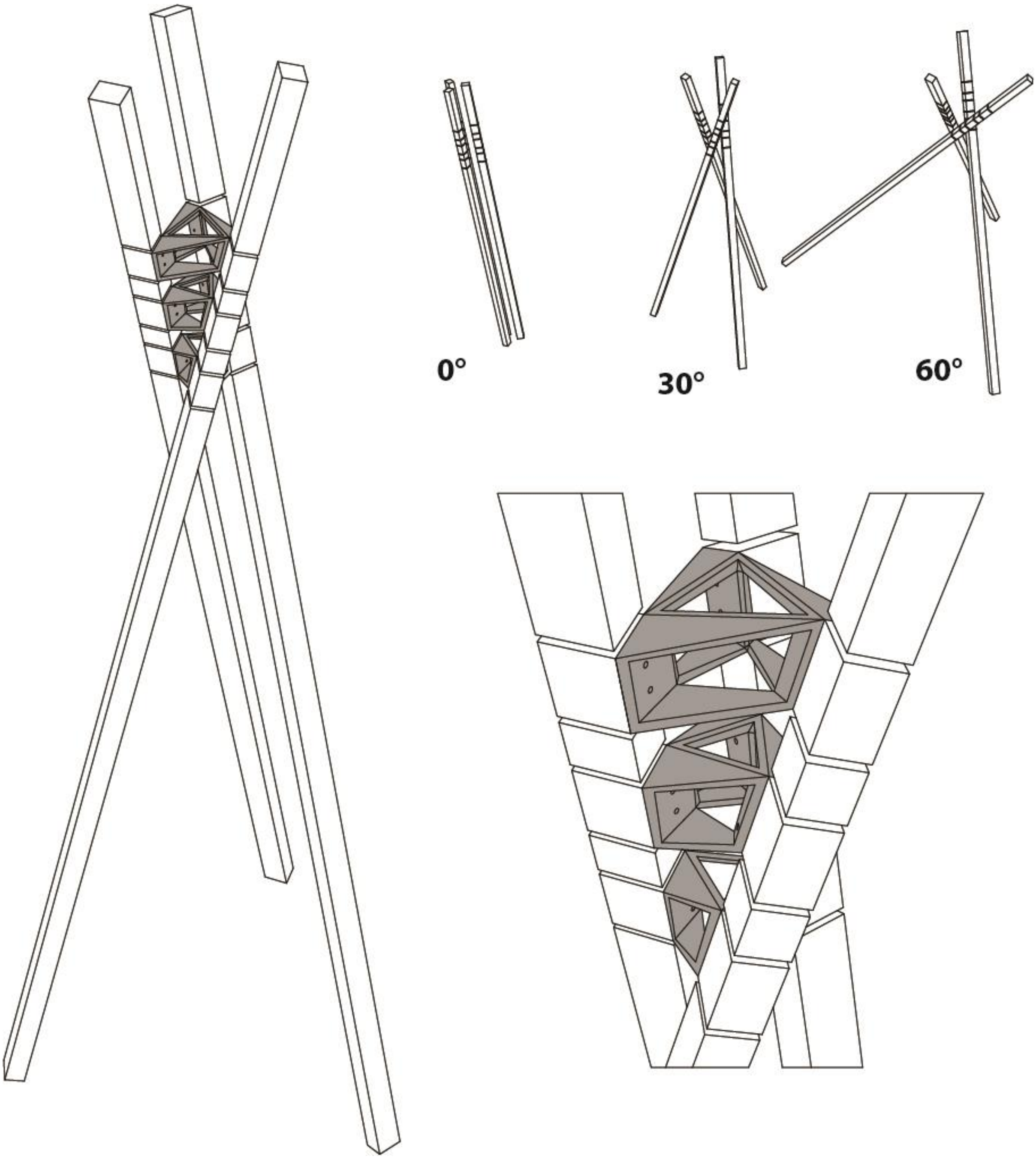

Figure 0.3. The genetic algorithm lets the user select the size and position of three poles. Next, it builds three volumes that connect the poles regardless its position.

Generative design allows the incorporation of more data inputs, collaboration and flexibility in a similar way as AM processes. McCormack et al. propose a dissection of generative systems that present complexity, interconnections with the environment, self-maintenance, and novelty generation. They categorize generative design methods in three groups. First, design through self-organization uses loosely coupled elements, or agents, that can make independent decisions according to their surroundings. These self-organized systems behave just like colonies of bees, flocks of birds, or schools of fish. Second, evolutionary systems, are composed by two sets of design functions. The generation function generates a population of results with the use of random parameters. Thereafter, the fitness function selects those generated designs that comply with the required adequacy. Third and last, generative grammars make use of “axioms” and “alphabets” to create sequences of shapes from existing sets of components. Shape grammars resemble a set of rules that transform the form of the object regardless its initial state. Through generative strategies, the result emerges from the interaction of system processes. Examples abound in the fields of product design and architecture where discrete units and processes are used with machine learning to create complex structures (*FABRICATE 2017.*, 2017). Generative design moves the role of the designer away from the exploration of the solution space. Rather, the designer manipulates the rules of exploration by creating an algorithm at a meta-project level. Meta-projects are an alternative to industrial ways of fabrication and articulates product individualization in a post-industrial scenario (Soddu, 2002).

The Tripod was created to increase the complexity of a product through the incorporation of 3D printed components that joined standard material available through hardware stores. The selected raw elements were 5x4 cm wooden poles/dowels. After exploring several configurations, the tripod was chosen as the starting module for its stability. Using Rhino 5.0 and its Grasshopper plugin, the sizes and positions of the poles were parameterized. Inside the design algorithm, the parameters can change to rotate and displace the tripod legs around the intersection centre. The algorithm selects surfaces at aligned levels of the inward faces of the poles as contact surfaces for the joint components. Next, it models a constrained group of volumes in the intersection of the contact surfaces regardless their position. The algorithm treats the volumes as continued surfaces from the edges of the contact surfaces and then processes them as triangle faces to give it a polygon shaped style. Finally, it locates the middle of the contact surfaces to position two perforations for two ¼” wood screws. The final algorithm could receive the pole parameters and the given space from a digital interface in a website. It should output three joints that keep the given poles together. The joints are aligned to the 3D printer layering direction to reduce structural stress and printed altogether. In the case of the printed example, the sizes and position were used to build a coat hanger Tripod (Figure 0.3 and Figure 0.4). Other pieces of furniture such as shelves or table scan also be derived from the same concept. The design would the access to 3rd party 3D printers in fablabs to offer a digital file that can be bought and downloaded for personal printing. As a proposal for business modelling, the Tripod meta-project uses generative design to offer a variety of products through the conceptualization of design rules.

Figure 0.4. Final view of the three volumes that are parametrized by the algorithm.

III. Finger splint (Topographic optimization)

The production of customized prosthetics for medical care has always been a promoted application of AM. This project looks for the creation of one prosthetic that is improved via structural optimization. Structural optimization is an important tool for the economy of designed structures. The main premise in optimization is the removal of material that does not perform under structural stress. Structurally optimized geometries are difficult to manufacture since they do not follow DFM practices. However, 3D printed products can fabricate the intricate results of structural optimization due to complexity freedom. Traditionally optimization has been inferred manually and until lately the incorporation of Finite Element Analysis (FEA) has helped to increase its precision. FEA builds a tridimensional mesh out of a CAD model and evaluates the structural performance of every element when the workloads are implemented in the structural component (Moaveni, 2008). With the incorporation of generative design tools, FEA can be used in the synthesis stage of the design process. The implementation of Finite Element Synthesis (FES) incorporates the input of FEA to reduce the density of the desired material by way of an algorithm. Later a second algorithm eliminates areas of the material that fall under a desired threshold. The result optimizes the geometry of designed components' topology and topography (Kilian et al., 2003).

FES can be implemented in different levels depending on the disposed manufacturing restrictions. Where manufacturing restrictions do not permit great modifications, FES can be used as an inspiration for the design of the final component. As the flexibility of the manufacturing process increases, the development of the component can approximate the final FES result. It is suggested that final AM components can parallel FES models (Stern, 2015). Other explorations of FES suggest that the input, which to this moment restricts to physical forces, could also be intervened by the designer as functional requirements of perception and semantics that could alter the density or composition of multi-material 3D printing (Oxman, 2010). Therefore, DFAM could also intervene in the composition of otherwise isotropic materials which is not a conventional domain for product design.

One of the core claims of AM implementation is the customization of human prosthetics. AM has the advantage of creating manufacturable solutions that fit individual bodies in complicated scenarios such as elderly and young patients (Groopman, 2014). An opportunity arose during the design of the research method to develop a finger splint for a mallet finger injury. Mallet injuries are deformations of a hand finger function where the extensor tendons get damaged accidentally (National Health Service, 2017). Mallet fingers happen frequently in sports such as baseball, basketball and volleyball.

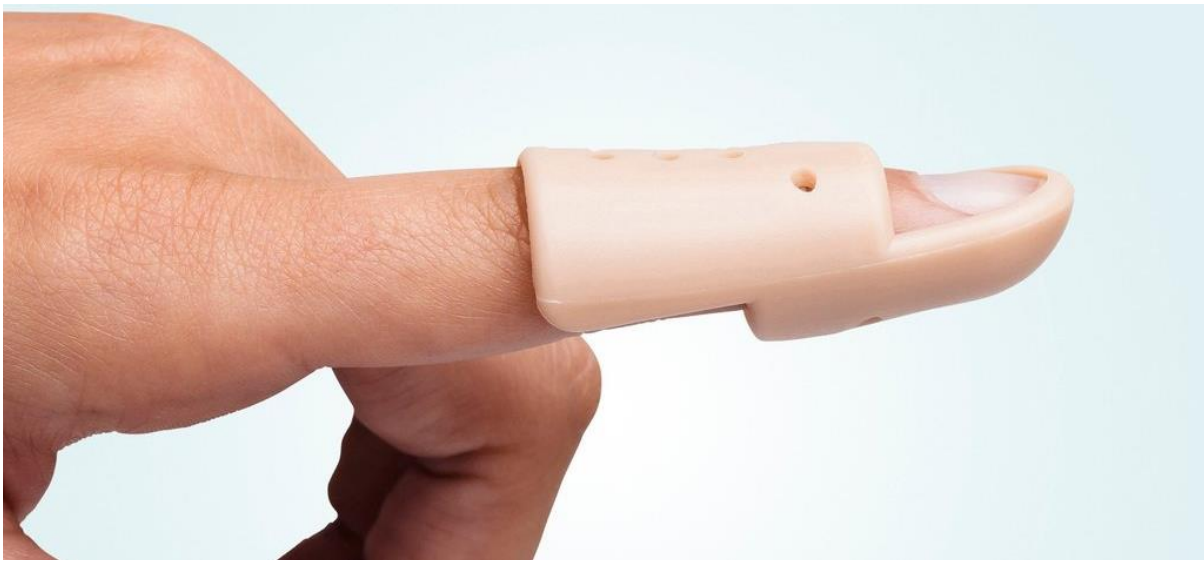

Figure 0.5. Common mallet finger splint (BeneCare Direct, 2019).

The treated injury occurred in a right hand ring finger and was a result of a volleyball injury. The variability of finger sizes makes mallet fingers difficult to standardize. Solutions are regularly sturdy and impede the performance of regular hand activities such as typewriting (Figure 0.5). The objective of the exercise was improving finger functionality while providing the same amount of protection and access. The exercise first modelled the profile of the injured finger using Autodesk Inventor parametric software (Autodesk Inventor 2020, 2019). Next, a functional volume was modelled around the finger figure to the limits of the functional available space around the finger. Inside the modelling environment, the volume was sectioned to determine the contact surfaces that other splints use as starting point for optimization. Maximum hand gripping loads were considered in the problem definition of the FEA algorithms. Several mass thresholds were evaluated from 45% to 65% every 5% reductions (Figure 0.6).

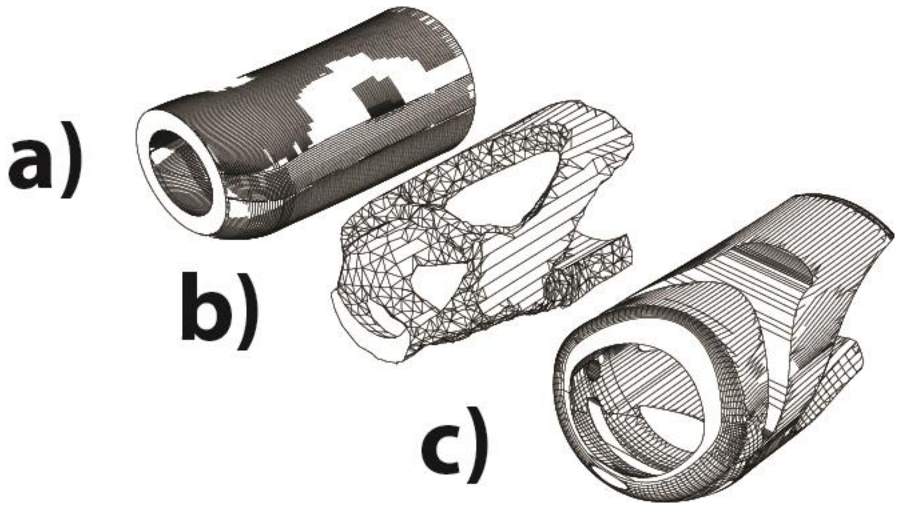

Figure 0.6. Structural optimization progression: a) Initial functional volume. b) Structural optimization result. c) Final optimization inspired result.

The final FES model was then 3D printed in FDM with Black PLA plastic and evaluated. FES algorithms suppose an isotropic material structure and thus the complex geometry of the result made force alignment difficult with the printer layering. Hence, the design was re-submitted to the modelling environment to improve structural strength in some areas and improve the comfort and style of the device. The final version demonstrates that the implementation of FES with AM is accessible through software yet relies on expert problem definition (Figure 0.7).The implementation of FES algorithms requires previous experience with structural optimization. FES removes almost all the acquired manufacturing complexity and lets the entrepreneur/designer handle the problem definition.

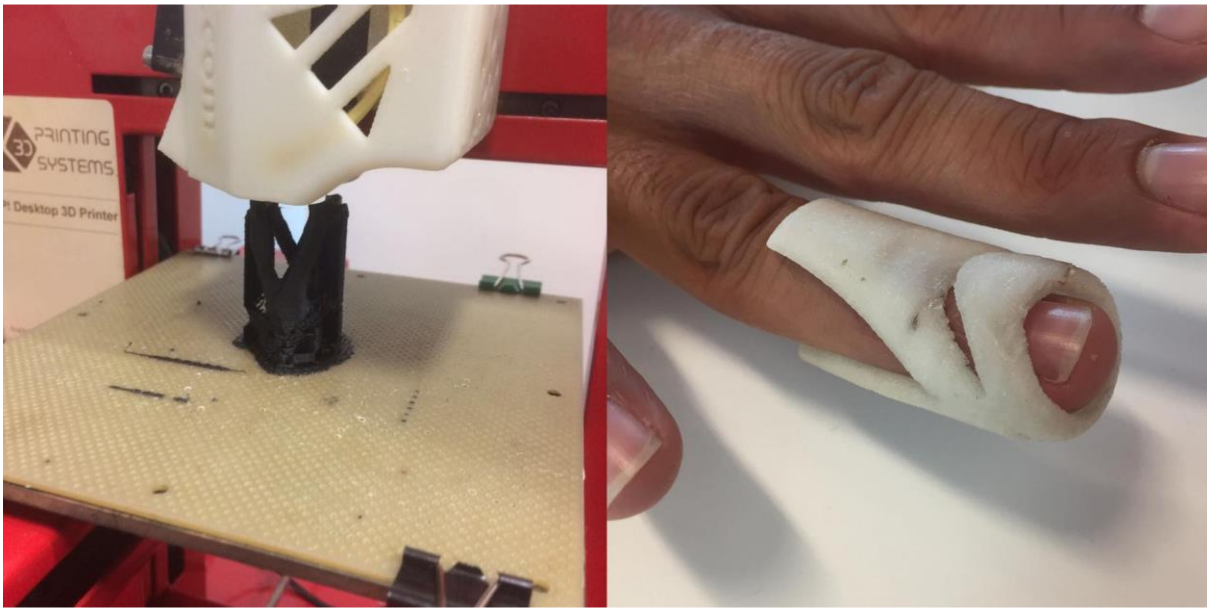

Figure 0.7. Fabrication and final finger splint.

IV. Cyggle (DFAM)

The greatest percentage of firms that use AM use it to develop prototypes of products that will later be manufactured through traditional methods. Thus, it is infered that the amount of products designed directly for AM is relatively small (Stern, 2015). The purpose of this exercise was to design a product exclusively for AM.

As discovered in the literature review, in order to design for AM, design and development processes must be aligned. This process level is difficult to implement. While FEA/FES deal with material and geometrical advantages, the advantages for the process are hidden in the inborn complexity of the problem (S. C.-Y. Lu & Suh, 2009). This inborn complexity can be considered merely functional and consequently describes the problem definition that designers create. Ponche et al. (Ponche et al., 2012) suggest that the main barrier for the incorporation of AM to the problem definition is the separation of design and manufacturing. Their proposal of coupled DFAM designs with the printer by letting it develop the structural shape that links the functional volumes. Hence, the definition of such volumes, which is related to the problem definition, is the most determining step in the design process. The Cyggle is an exercise that looks for the incorporation of seemingly not related objects and activities in a DFAM problem space in order to design with, and not for, AM.

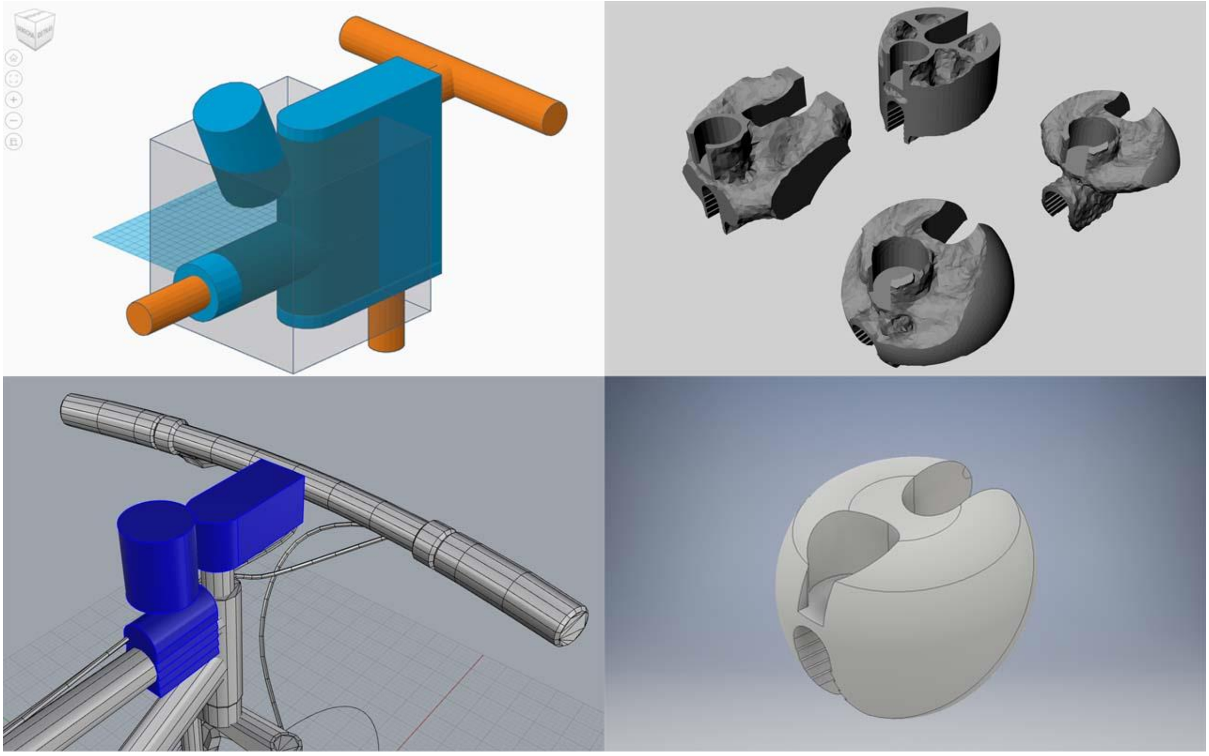

Figure 0.8. Transition from the determination of fucntional volumes in a bicycle 3D model to the topographic optimization.

In collaboration with the Ballerup Public Library in Ballerup, Denmark, a short workshop was ran around this concurrent perspective of DFAM. The workshop focused in the ability of the printer to incorporate more functional surfaces and volumes as long as they fit in the printable volume. In a public FABLAB context, this ability has the potential of incorporating more stakeholders in the fabrication of a solution to a shared problem. Thus, in order to demonstrate that even the objects and stakeholders that seem completely unrelated can fit into one solution, a creative activity usually known as forced analogies for product ideation was proposed. The activity looks for creative ideas to link two semantically distanced concepts by forcing relationships amongst them. The used concepts in the activity were “cycling” and “Danish Christmas pastry”. After a round of voting, the winning concept was a device to help drunk cycling in Denmark. Following Ponche et al., the development of the object started with the definition of functional volumes, which in this case considered a surface to fix the device to the bike frame, two surfaces to limit handlebar movement, and a volume to hold a beer can. The surfaces and the printing volume were modelled in Autodesk Inventor environment and submitted to FES evaluation (Figure 0.8). Once unnecessary material was removed, the volume was re-created in alignment with the FDM printer layering direction. Finally, a mechanism to incorporate flexibility to the volume was cut from the volume (Figure 0.9). The result demonstrates that the DFAM proposal from Ponche et al. can easily be implemented with the support of design expertise. Likewise it demonstrates again that problem definition is the most influential input for the implementation of AM.

Figure 0.9. The final version of the Cyggle merges the unrelated products of a bike and beer and creates a new functionality.

V. Turtlebag (Complexity afforded outside AM)

All the examples shown above suggest that the removal of acquired complexity in AM processes opens the design process for the inclusion of more complex functions. The last design exercise is centred in the broader interpretation of this new functionality available in AM processes. The exercise consisted of a speculative design exercise in collaboration with the Additivist Manifesto. Additivism is a project from artists Morehshin Allahyari and Daniel Rourke that looks critically at the appearance of 3D printing as a democratized manufacturing method. Additivism (a name that is a *portmanteau* of additive and activism) focuses on the potential that the 3D printer has as an interface to alter our material reality (Morehshin Allahyari & Daniel Rourke, 2015). They portrait the 3D printer as a medium compared to photocopiers that during the 1960's and 1970's were used to transgress intellectual property and share content to power social movements. For Additivism, the 3D printer is a metaphor for the ability humans have developed to alter their environments and bodies. AM brings to Additivism the potential of immediate complexity instead of free complexity seen in manufacturing. Immediate complexity allows the printer user to transgress the configuration of matter to merge and experiment without the restrictions imposed by social structures such as capital and discourses. This immediateness brought by AM brings the agency that belongs to organizations to individual agents. AM permits users to complement and alter their surrounding to the extent where it is possible to talk about a literal fusion between the natural and the artificial (Groopman, 2014).

Allahyari and Rourke also reminds us that these transformations happen mostly using plastic. These small-scale transformations of our immediate environments connect, through the 3D printer, to the macro scale of human caused changes in the environment in the age of the Anthropocene. For the additivists, the 3D printer has the potential of leveraging the actual results of the technology as much as the elicited metaphors in multiple discursive directions. The Additivist project seized inspiration in the creation of the anarchist cookbook (Powell, 2016) to create an "Additivism cookbook" that gathers subversive and disruptive projects that question and leverage the impact of AM. The turtlebag is the result of the collaboration with the additivists in a workshop carried out at COLAB in March 2016.

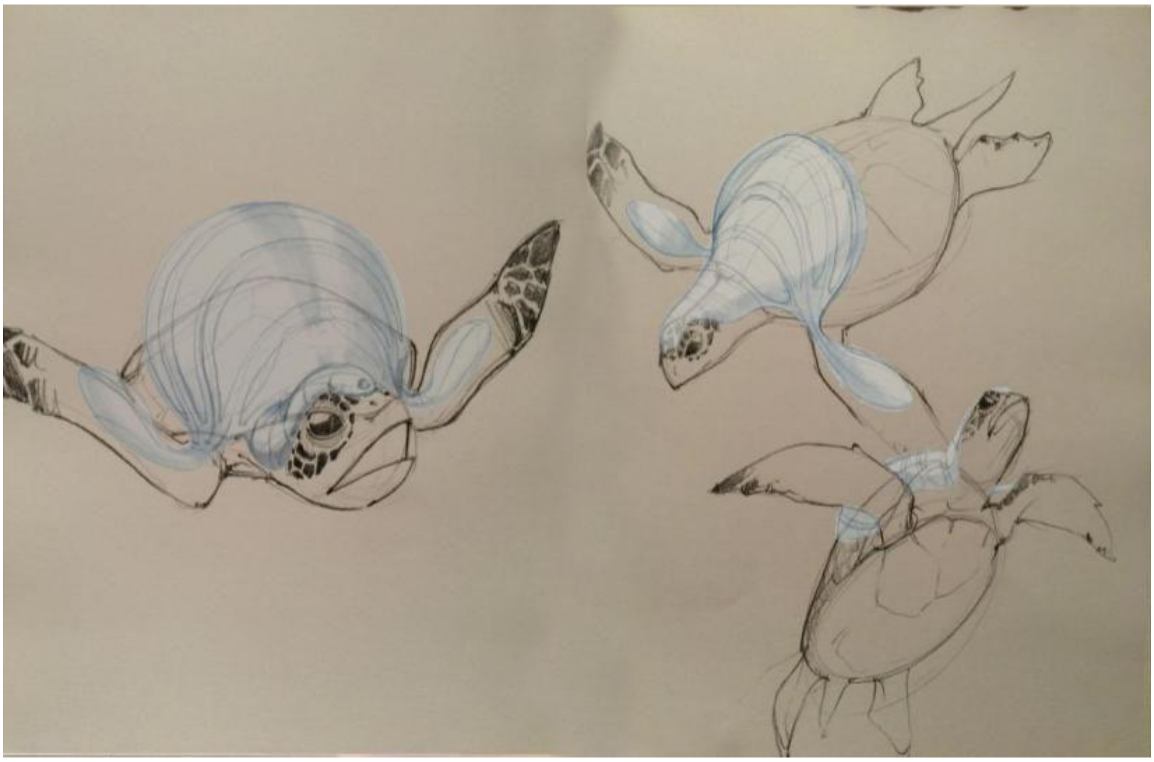

Figure 0.10. The initial turtlebag sketches show a a3D printed appendix for turtles to separate plastic from jellyfish.

The turtlebag speculates the design of a complex artificial stomach that could be 3D printed and placed as an artificial organ over the turtle shell (Figure 0.10). It draws inspiration from the pervasiveness of plastic, the impact it can cause at a geological level (Boetzkes & Pendakis, 2013), and Donna Haraways's concept of "Chthulucene" (Haraway, 2016) . Contrary to the Anthropocene, the Chthulucene is a proposal to embrace the changes that human action has on the planet instead of trying to fix them from an anthropocentric view. Haraway invites humankind to compost with that which is considered waste and digest the coming future. The turtlebag questions whether to leave the affected species of the ocean as they are or alter them with the immediate complexity of AM to help them cope with change.

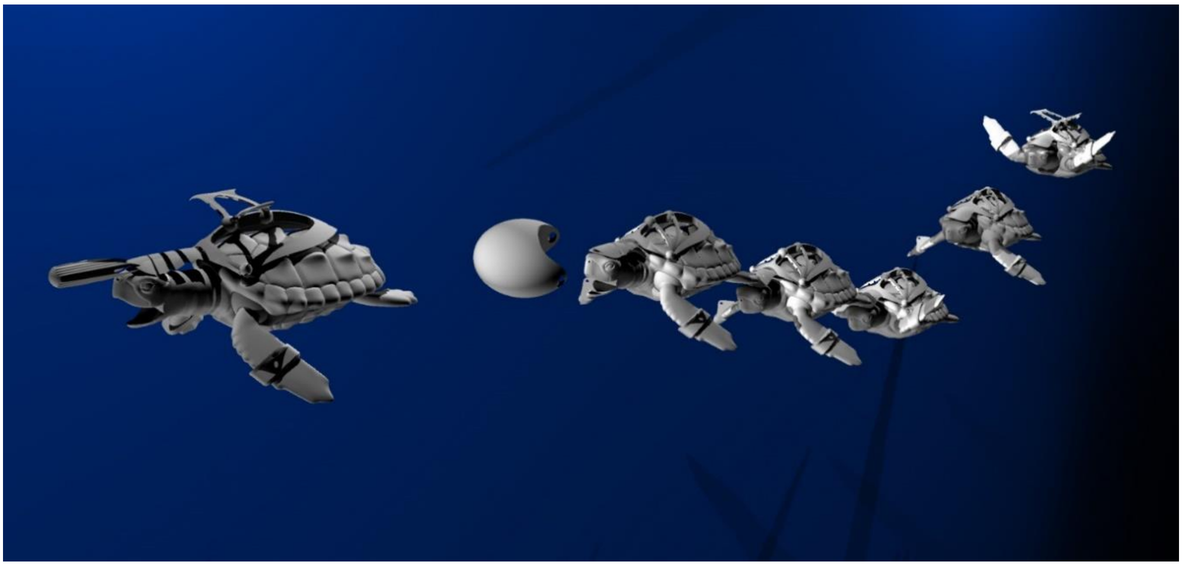

Figure 0.11. Sequence of turtlebag function (without cover).

The turtlebag addresses the problem brought by the inability of turtles to differentiate plastic bags and jellyfish. Research estimates that a third of turtles that die stranded in the coasts of New Zealand die due to the ingestion of plastic bags (Godoy, 2016). Thus, the device has the objective of separating plastic bags from jellyfish before a turtle can swallow it. The device is composed by a system of two cavities that swallow plastic communicated to a “mouth” on top of the turtle’s head. Both cavities have a unidirectional valve system that operates like a water pump and two ribs that permanently expand them creating a suction action. The system forces out water from the stomachs by bending the ribs with the turtle flapping (Figure 0.11). Since the valve system only operates one way, the stomachs remain compressed and the ribs bend storing energy for the suction. The system activates when a turtle spots a plastic bag and stretches its neck to bite. The movement stretches the valve and opens it letting the ribs expand and suck the plastic bag before the turtle has the chance to swallow it. The turtlebag differentiates plasticbags from jellyfish because jellyfish are not compressible while plastic bags are. A jellyfish would get stuck in the “plastic mouth” letting the turtle eat its pray.

The turtlebag was selected for two subsequent exhibitions in the Onassis Cultural Center in Athens, Greece (Daphne Dragona & Panos Dragonas, 2017) and MU art space in Eindhoven, The Netherlands (Nadine Roestenburg & Angelique Spaninks, 2017)(Figure 0.12). The turtlebag is a speculative proposal that makes use of multi-material printing available today in smaller scales. It is an example of the consequences in the macro level of change that AM literature does not consider traditionally but affects other domains than the manufacturing process.

Figure 0.12. Version of the turtlebag concept exhibited in MU Art Space, Eindhoven, The Netherlands.

Appendix B: The Shape of Firms: Opportunities from Rapid Manufacturing

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Abstract. This paper examines the role of design in the creation of new firms. A new interpretation of firm design is developed to explain the dynamics of entrepreneurship. This paper seeks to expand the conversation between design and management studies by focusing on the concept of shaping the firm. The study of the shape of the firm seeks to characterise the dependencies between the features of products and the organizational possibilities of new firms. We intersect theories from the fields of management and design theory to examine the shape of the firm in the entrepreneurship context. From this study, opportunities are identified for research approaches to address the entanglement between the shape of the product and the shape of the firm. Implications for practice are discussed.

Keywords: Firm Design, Entrepreneurship, Digital Technologies.

I. Introduction

The role of design in the creation of new business ventures has been documented in the academic and professional literature [1, 2, 3]. An alternative design approach to entrepreneurship considers it as a matter of firm design [4, 5], a process of creation of artificial means that negotiate with the environment. We suggest that more nuanced descriptions of firm design are needed. This paper frames the study of the shape of the firm based on the intersection of design science, entrepreneurship theories, and rapid manufacturing technology. First, we examine the roles of design in the creation of new business ventures and describe shape as the formal dimension of firm design. We then examine theories of firm creation applying an ontology of design activity, the Function-Behaviour-Structure (FBS) framework, to elucidate a space for the shape of the firm. The relationships between the shape of the product and the shape of the firm are analysed. Finally, we formulate a set of questions for the study of this entanglement in new business creation to empower future entrepreneurs to identify and capitalise on these relationships.

II. Expanding Design & Management

Entrepreneurship theories are strongly influenced by assumptions in management studies about the purpose, object, and process of creating business ventures. Two strands of thought are represented in the role of design in entrepreneurship: Strategic Design (SD) and Design Thinking (DT). SD is a branch of strategic thinking concerned with the creation of idealised plans for the optimal accomplishment of objectives. SD is distinguished for generating a carefully controlled process of thought, centralizing planning in the figure of the strategist, simplifying an original, complete, and explicit outcome, separated from the implementation process [6, 7]. DT for strategic planning has gained popularity as a tool for integrating divergent (synthetic) and convergent (analytic) reasoning. DT is mainly used for the synthesis of solutions based on abductive logic, the exploitation of opportunities, and the use of inquiry for value generation [8, 9]. It is the intention of this proposition to expand the definition and applicability of design principles in management based on the study of design activity.

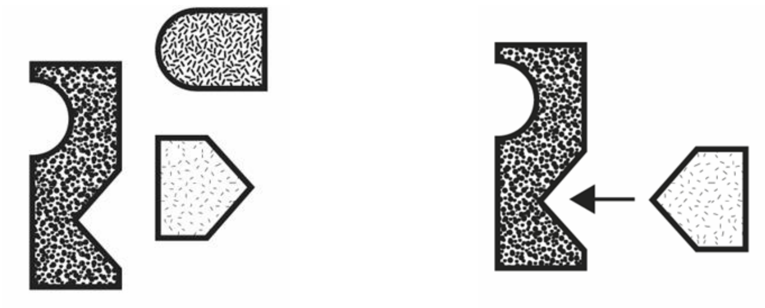
Design has been defined as the capacity of “conceiving, planning, and making products that serve human beings in the accomplishment of their individual and collective purposes” [10, 11]. In other words, design is a process that uses the creation of artefacts to interact with the environment and effectuate desired results. Designed artefacts create new practices and as a consequence new identities of those who use [12, 13, 14]. As an activity of creation of our desired future state, the scope of design covers the production of all human artefacts, such as firms, from very diverse perspectives different from SD and DT.

Understanding firms as products of their products, designs can be understood as first-order principles of [15]. Therefore through design, managers are in charge of creating value within the firm in order to achieve differentiation. This view aligns with Sarasvathy’s perspective of entrepreneurship. Based on the study of expert entrepreneurs, she portrays the entrepreneurial process as the effectuation of negotiations that helps entrepreneurs in the achievement of their goals [16,17]. Specifically, she highlights the need to research the processing of language and the categorisation of symbols in the entrepreneurial [5]. The behaviours around artefacts related to the firm, such as brands, logos, products, etc. imply that the firm is an artefact that can be studied at a semantic level. Therefore, the study of design opens new opportunities for the study of the entrepreneurship process resulting in the design of a firm like an artefact.

i. Artefacts of Design

Artefacts are the object of design. In order to modify our environment, we interact with artefacts through their shape. Human ecologies, like other ecologies, are defined by the spaces or fluids that enable the movement of substances [18]. Medium and substances are separated by surfaces which have specific layouts that we call “shape”. Shape configurations gather properties that help us distinguish them and give them a specific character i.e. room, chair, cloth, bank, or [19]. Through shape, artefacts relate within the semantic ecology of our environment, as illustrated in Figure 1a. Shape communicates the counter-ability of artefacts, or the available purposes and actions that we can perform with the artefact. Through shape, artefacts help us in the accomplishment of the objectives of their design, as illustrated in

Figure 1b. When designing an artefact, designers refer to the perceptual grammar that resembles the possibilities of creation within a specific typology of artefacts.



a. An ecology is composed by substances and a space or medium

b. Shape limits the substance of the artefact and signals its counter-abilities or affordances (Gibson, 2014)

Fig. 1. Shape ecologies.

Due to the complexity of human production, the shape of system artefacts can be difficult to model. The creation of transactional systems lacks a formal manifestation compared with the design of physical artefacts. Therefore, the relationship between users, the environment, and firms as artefacts is not bounded by visible appearances, but by conditions of scale and reciprocity. Scale determines the span of interaction while reciprocity is the correspondence between the artefact and the user's interactive capabilities [20]. This is evident in the development of designed objects and spaces where the corresponding relationships between our bodies and the artefacts are found in the size of doors, or the roundness of handles. It is evident that in the case of complex systems such as firms, the scale and reciprocity shall be difficult to detect. We can infer that today in the design of business we experience a mismatch between the shape of the business and the relationship that it has to our human bodies and minds. When does our interaction with a business start and end? What are our expected behaviours? What is the vocabulary of the firm that we are meant to interpret?

Today the brand and its touch-points, as well as the product, and the packaging, are considered [21]. Nevertheless, a close examination of the existing theories of the firm suggests that the elements that compose a firm could be a designable as well. For instance, the theory of transaction costs considers that the firm will try to include all the transactions that increase the complexity of operations and as a result, increase cost. A model of the shape of the firm should attempt to account for these manifestations, and develop a designable perceptual grammar of the firm.

III. The Shape of the Firm and the Theories of the Firm

Current descriptions of the firm suggest the relational nature of business enterprises. Usually they account for heterogeneous compositions of resources, knowledge and human capital. Nevertheless, the firm as an artefact must also be justified as an effectuative prosthetic of human bodies. Consequently, it must have a reciprocal relationship to our scales and perceptive boundaries. The shape of the firm needs to be designed to afford specific behaviours on users according to the business logic and objectives. Customers, partners, employees, entrepreneurs, managers, stakeholders, and other artefacts interact with the affordances that the shape of the firm presents. The firm may interface through symbols and systems (brands, products, etc.) to elicit the desired behaviours of the business strategy. Therefore, inasmuch as the term user extends to all the people that interact with the signifiers of the firm, the quality of a good or bad firm design could be defined not only for its relative performance, but by the difference between the expected behaviours of the design and the real behaviours that are elicited in users through these symbols. A different typology of firms based on shapes, could generate more options for business design and innovation creating more mechanisms for differentiation. However, in order to articulate a model of the shape of the firm, the existing theories that describe the composition of the firm space should be situated in design terms.

i. The FBS Ontology and Framework

The FBS ontology [22] is a useful to describe the design space and has been used extensively to model design [23, 24, 25. Its ontology organises design based on three fundamental constructs: Function, Behaviour, and Structure. Function is described as the teleological cause of the artefact, or the relationship between the goals and how they are met. Behaviour describes the performance derived from the artefact's structure. Structure refers to the arrangement of the artefact's components whether they are physical, virtual or social. Behaviour can be derived from structure using physical laws or heuristics, whilst no direct connection exists between function and [26]. The FBS framework splits the artefact space in two; the expected world, and the interpreted world. In the expected world, users and designers make up expectations of the artefact to be based on perception. Differently from users, designers enact this expectation in the design process. The interpretation world includes the artefact's use. Interpretation does not always aligns with expectation. An expected function (Fe) inductively derives an expected behaviour (Be) and an expected structure (Se). The materialised structure (S) elicits a behaviour (B) which in comparison with the design goals reveals a function (F). The FBS schema is depicted in Figure 2. The distance between these two processes expands the set of transformations from a linear transformation, to a set of iterative processes that reflect many design processes, from the generation of requirements to the interpreted description of the artefact.

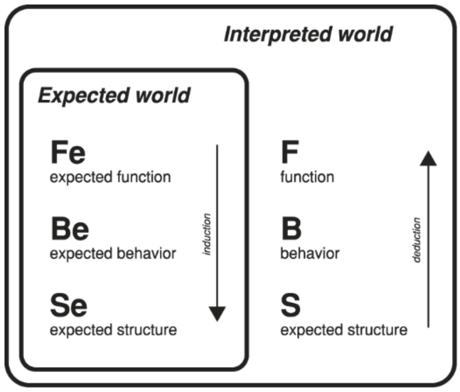


Fig. 2. The FBS framework supports a model of design processes [22]

Three groups of theories that account for the nature of the firm in economic sciences can be situated within the FBS framework to yield a different understanding of the firm as an artefact. Firstly, the theories of the firm, which account for the purpose and nature of the firm against market structures. Next, the models of enterprise ontology, originated as a tool for representing the entities and activities related inside a business. And finally, the theory of business models which explains the logic that underlies value creation and delivery. While each of the groups is formed by multiple models and theories, we consider their shared features.

First, the theories of the firm can be considered as a group centred in the description of a meta-level of abstraction. The purpose of the theory of the firm is to define the formal relations that differentiate it from the market and industry structures in a way that contributes to the study of economics [27, 28, 29, 30, 31]. Consequently, the models that the theories of the firm supply, are strongly related to the expected function (Fe) and behaviours (Be) of the firm. Coase [28] makes evident the question of the firm purpose, i.e., “why is there any organisation?”. Similarly, theories of the firm attempt “first, to specify the decisions that business firms will make (as a basis for more aggregate predictions of the economy) and second, to prescribe appropriate decision rules for a rational firm operating in a market economy” [32]. Overall, these theories seek to describe an ontology of the firm based on the observations of business, ergo showing interpretations of it as a phenomenon, not an artefact.

The majority of these theories account for functions that were based on the economic assumptions of supposed homogeneous goals of the entrepreneur and opportunism. In the design of new businesses, a tension is observable between the predefined layout of these expected functions and behaviours in economy, and the goals that individuals could bring to firm creation. Theories of creative entrepreneurship such as creative organizing [33] and bricolage [34] do not fit the theories of the firm. These theories do not show relationships that are able to induce structures and behaviours of the firm beyond the existing paradigms of economics and management. Moreover, the conflict between supposed heterogeneous goals and behaviours evidences a void in the theories of the firm that if addressed could create more possibilities for firm design.

Despite being a detailed reference of business entities, enterprise ontologies fail to map the firm onto a structural level. The diversity of models around enterprise ontologies can differ but they all concur in the representation of the entities to be monitored in order to exercise control of the company. Fox & Gruninger stress the role of ontologies in the integration of the enterprise by the addition of subsets of specific ontologies; “for example, the notion of manufacturability requires reasoning about the product’s properties, preconditions, and effects of activities and the capabilities of resources” [35]. Therefore, business ontologies seem to be a reference tool for performance accountability rather than representing the structure itself. Yet, as legal litigations show, not all the affordable behaviours through the firm are accounted by business [36]. Therefore, if we consider that design theories of artefacts recognise the interpretation of the user in the redefinition of the purpose and its interaction with the context in the creation of affordances, an enterprise ontology mistakes the role of human entities in the exercise of creativity and innovation.

Business models show the logic behind the operation and profitability of a firm [37]. Research and popular literature consider that the design of a business model is essential in the early stages of the entrepreneurial process. Situating the business model definition within the FBS framework, the business logic fits the expected behaviour (Be) around the designed artefact. The activity based design process of business models proposed by Zott & Amit portraits the business model as a blueprint for the derivation of the firm structure [38]. Accordingly, Osterwalder and Pigneur situate the business model as an organising matrix inside the firm. They argue that the interaction between the business model, strategy, information, and organisation guides the firm's operation. The manifested business model of a company becomes a tool for the communication of strategy [39]. Hence, it could expand itself from the expected, to the interpreted behaviour since it elicits specific actions (at least at a macro level) in the exercise of the firm. Nevertheless, since there is no object to refer as a firm artefact, the deduced behaviours can be forced through explicit strategy and could be understood as ambiguous.

The resulting mapping of theories of the firm, enterprise ontologies and business models in to the FBS framework is shown in Figure 3.

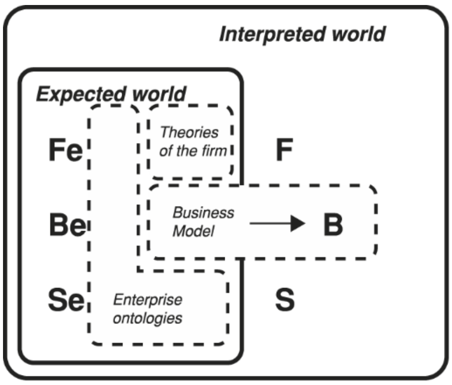


Fig. 3. The existing theories that describe firms only consider one "natural" firm structure that is pushed to the interpreted world through strategic communication.

The Entangled Shape of the Firm

The theories of design and management examined here show the extant need for defining the interpreted world of the firm artefact. Literature on product architecture has interesting developments that consider the interaction between the firm and its users. Based on evidence of the relationship between product architecture and the success of firms, these studies confirm that the division of labour in firms reflects the principle of bounded rationality and consequently mirrors the configuration of the product into the information processing structures of the firm [40, 41]. As a consequence, the arrangement of the product architecture can affect the organisational learning curve and the exercise of authority between organisational divisions [42]. This *mirroring process* suggests that the development of information mechanisms that support product architecture solidifies and extends through time beyond the firm and into its suppliers and the rest of the industry [43]. Different products predefine available organisational configurations regardless the imposed strategy. The inadequate mirroring of a product architecture in the early stages of business development may carry associative thinking biases that need to be tackled through iterations of divergent configurations of the product and value proposition [44, 45]. The mirroring effect implies that one of the most important strategic choices in firm creation is the relationship between the components in product architecture.

As Sarasvathy proposes, entrepreneurship can be considered as the design of a firm artefact that aids entrepreneurs in the fulfilment of their goals. In the design of the firm artefact, a range of participants as users are acknowledged: Customers, suppliers, employees, etc. Consequently, possible misinterpretations of individual roles inside corporations need to be considered. Errors in the use of an artefact, such as pulling a door when it needs to be pushed, or walking over “lines of desire” in gardens and parks instead of going around the corner, are design flaws. Similarly, behaviours like delayed payments, product order misunderstandings, quality issues, and fraudulent practices, could be caused by affordances in the firm that are not accounted for. Moreover, desired behaviours focused on the creation of value and innovation could also be elicited through the design of the shape of the firm.Based on the mirroring process between product and organisational architectures, the main argument of this proposition is that the shape of the firm is composed by the dependencies between functional components in product architecture and organisational configurations which evoke the behaviours of firms users. Therefore, in the firm design process, the conceptualisation of different dependencies in the shape of the firm will make available specific product and organisational possibilities that can be matched to the goals of the entrepreneur. This approach is different from conventional innovation and entrepreneurial processes which create a product, and force an expected behaviour of users through strategic communication. Hence, current tools operate under the assumptions of the theories of the firm, business models and enterprise ontologies, regardless different product architectures. This new approach opens new opportunities for the creation of methods and tools that articulate the shape of the firm according to its interaction with humans, and other artefacts (logos, brands, media, other firms, etc.).

Just as the guidelines in the shape of a chair artefact, the dependencies between components and teams resemble the shape of the firm artefact (Figure 4a). Traditional entrepreneurship takes the design of a product and enforces organisational behaviours through strategy (Figure 4b). Through the design of the shape of the firm, product architectures can be purposefully selected that correspond to organizational configurations (Figure 4c).

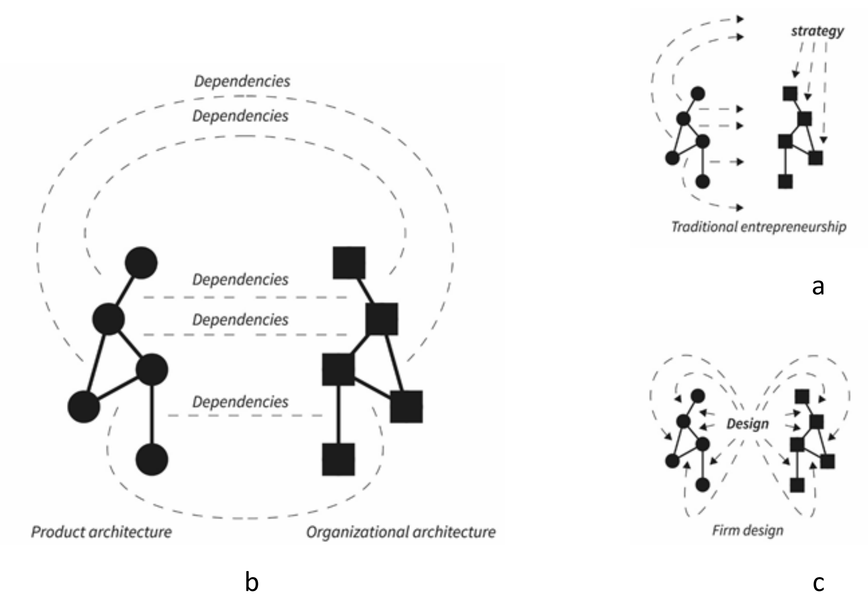


Fig. 4. Mappings of dependencies between product and firm design.

Rapid Manufacturing and the Shape of the Firm

This proposition is especially relevant today in view of digital technologies. Information Technology based tools summarize in code structures that before required the commitment of valuable resources. As a result, firms today are more flexible than before [46]. Tools that now are used for around the business model, such as enterprise application, customer relationship management, and computer aided design software can be modified to fit and interact with the shape of the firm to bring out desired behaviours in users and feedback relevant data for the iteration of the shape itself. Tools for data science, such as mining and analytics can help in the shaping of the affordable relationships in the geometry of the firm. With the involvement of data, generative algorithms of design could be used to adopt a flexible strategy that take advantage of contingencies and react instantly to social and market fluctuations. Technologies like A*dditive Manufacturing* (AM) could project this digital flexibility to the production of material goods. Algorithms of generative design, can adapt the shape of produced products to the desired affordances of the shape in real time. Manufacturing of goods can be as flexible as needed for the business to effectuate the acquisition of partnerships and resources.

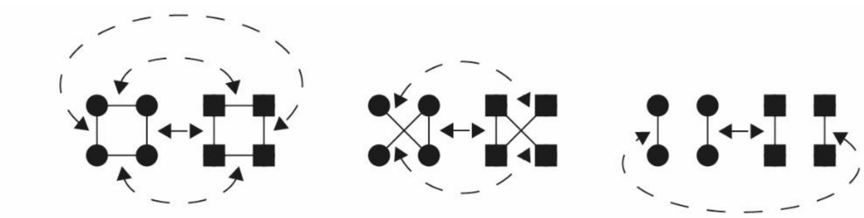


Fig. 5. Additive manufacturing could enable the exploration of different shape configurations without heavy capital investment.

For entrepreneurship this is an opportunity to leverage the relationships and shape the firm through the initial product according to the final goal of the entrepreneur. This will expand the role of design and the available control of the entrepreneur over the firm's future. Traditionally, regardless the industry, entrepreneurship processes are conformed by a discovery, evaluation, and exploitation of the business idea [47]. By integrating digital technologies, this processes have become more agile in the implementation and evaluation of explored ideas. Nevertheless, this processes guides itself through trial and [48, 49]. A model of the shape of the firm could inform the implementation of this experiments in a more purposeful and specific way. It would integrate strategy to the production of the goods immediately in a way that is particular to the product that is being fabricated. Therefore, strategy could use digital technologies to extremely detail and micro-manage the shape of the firm. Unique paths for differentiation could originate in the interaction between the entrepreneurial contingency and the project that could push the competitiveness of small firms in front of competing corporations.

Experimentation with alternative concepts of digital business can be brought forward thanks to a model of the shape of the firm. While companies usually rely on the same structure, different shapes of firms could experiment with concepts that current ones find very expensive to use. That is the case of distributed manufacturing, a model where automated manufacturing like 3D printing could fabricate goods in smaller facilities distributed geographically. Despite the potential saves in cost, research has proven to be difficult to [50]. A specialized design of the shape of a firm could leverage the creation of networks that make this model possible. Other explorations with cryptocurrencies or “money of the commons” could also be matched to shapes of firms. Shapes that facilitate stakeholder governance mechanisms could make use of such technologies to foster social entrepreneurship.

IV. Conclusion

Expanding the idea of firm design beyond the creation of instruments for strategy (SD & DT) to firm design creates a vast space for the exploration of the firm as a designable artefact. Artefacts as prosthetics of human bodies help us modify our environment to match our desired goals. Likewise, a firm artefact would help the entrepreneur to effectuate the contingencies that surround the project and fulfil specific purposes. After an analysis of current theories of firm creation, this paper identifies a void between the expected behaviours of the firms and the interpreted behaviours inside it. There seems to be no guided action outside the communication of strategy and as a consequence, the existing theories do not account for all the afforded behaviours in the interaction between the firm and its possible users. Based on the evidence from studies on product architecture, we propose that the shape of the firm can be found in the dependencies between the product and organizational architectures. Therefore, by designing a specific set of dependencies, the product and organizational architectures of the firm could be mutually defined.

The study of the shape of the firm brings together the study of entrepreneurship and design. Processes of entrepreneurship could make use of design to articulate different shapes according to specific goals attainable by the entrepreneur. Tools for creative entrepreneurship could be designed to take advantage of the distinctive conditions of each entrepreneurial context. This would help grounding popular tools like business modelling on the entrepreneur's reality and give more certainty to projects that do not have access to venture capital or even information technology means. Shifting focus to technology based entrepreneuring, a theory of the shape of the firm would give a very valuable resource for start-ups to adapt and react based on the integration of data feeds to the design process of the firm.

This study also identifies opportunities for the study of the perceptive grammar and the resulting typologies of firms. Different types shall be classified according to size, industries, products, value propositions etc. Dependencies of the firm could be also classified according to their function. Making use of analogical reasoning from biology theory, the main dependencies for the growth and reproduction of the firm could be theorised. Start-ups could be designed to act as dynamically as viruses, or rely on high memory and learning capacity like elephants and insect colonies. Industries could be studied according to the interactions within firms, viewed as ecosystems. Firms could be designed to create relationships of competition by cultivating dependencies that tie them to strong yet flexible networks of firms and users. Extending the analogy, firm and product differentiation can be achieved based on strategies of lifespans, replication, ecological inheritance, niche construction, and mutual adaptation [51] (Sterelny 2004).

This paper closes with three areas of interest for original research around the aesthetics of firm-artefact relations. First, the role of the product needs to be studied in the context of the evolution of the firm structure in the entrepreneurial process. This will permit the representation of the dependencies between the two structures in a practical context. Second, different shapes of firms need to be explored with the aid of rapid manufacturing technologies. Just as we can explore the shape of product design, we must explore a language that represents accurately the entanglement of the architectures and the guidelines of the shape as a whole. As mentioned before, rapid manufacturing technologies are notable for their flexibility. Therefore, by making changes in product architecture using additive manufacturing, it would be reasonable to expect to induce the dependencies and map the families of firm design. Finally, expanding the research around product architecture, the development of cases that analyse the interaction of firm shapes such as the failure between Boston Dynamics & Google [52], the adoption of Snapchat features by Facebook apps [53], or new product development in game consoles [54]. By considering these three possible routes of inquiry, the study of the shape of the firm has the potential to leverage design in the creation of more deliberate futures for entrepreneurs and new businesses.

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Appendix C: Entrepreneurial Ideation - Mirroring Effects of Morphology and Complexity

I. Introduction

Studies of product architecture and effectuation in entrepreneurship suggest that product architecture can be leveraged within entrepreneurship to design new organizations. Product architecture refers to the structural arrangement and allocation of functions from the physical components of a designed artefact and their interfaces (Ulrich, 1995). Some studies describe a relationship between product architecture and the performance of products and firms (C. Christensen, 2013) and others also identify a mirroring process between the product and the organisation structures (Colfer & Baldwin, 2016). Effectuation in entrepreneurship portrays the creation of markets in a similar fashion to the theories of mirroring (Sarasvathy & Dew, 2005). In effectuation, the accumulation of stakeholder commitments around the product assembles new markets. Therefore, a flexible product design can leverage changes in product architecture with the purpose of establishing particular partnerships for the entrepreneurial venture.

This paper presents an analysis of the effects of the complexity in the product structure on *entrepreneurial ideation*. The study focused on the operationalization of complexity in product architecture. However, the analysis of an ideation survey suggests that design complexity may not be as straightforward as previously assumed by studies of architecture mirroring. Whilst findings indicate no effects of complexity in entrepreneurial ideation, a shared language is revealed in the interpretations of images of different complexity levels. We argue that this shared language is a consequence of the morphology of the images used in the study and discuss implications for the study of entrepreneurial ideation.

II. Background: The *mirroring process* of product architecture

Early models that connect product and organization structures portrayed products as systems that solve complex functional requirements (Ulrich, 1995; Murmann and Frenken, 2006). During product design and development, management faces a coordination problem: the effective allocation of design resources for the solution of such requirements. Accordingly, those models propose breaking down complex systems in subsystems assigned to different teams, following the relationships of functional requirements. As such, a product is characterized as a system with visible or hidden interconnections of components arranged in near-decomposable subsystems that correspond to functional requirements. The modularization of complex problems generates a hierarchy of problem solving teams that defines interfaces between the design components and communication channels between teams in charge of them (Conway, 1968). Problem modularization reduces the possible interdependencies that larger and more complex systems create, thus making a more effective use of resources in design tasks (Sanchez & Mahoney, 1996). For example, modularization allows concurrent learning cycles while integral designs rely on sequential or overlapped programs. Later applications of this idea in the study of manufacturing introduced the concept of product architecture and began studying the effects on product, design team, and firm performance.

Studies of technology management have addressed the effects of product architecture from a broader perspective. Based on frameworks that describe innovation cycles, researchers have explored the degree of change in performance dimensions such as design knowledge, architecture, or market maturity (C. M. Christensen & Rosenbloom, 1995; Henderson & Clark, 1990; Murmann & Frenken, 2006). It has been suggested that early architectural subdivisions of artefact functions are gradually mirrored to the structure of the industry and its participants i.e. suppliers, distributors, regulators, etc. (Colfer & Baldwin, 2016). Christensen and Rosenbloom (1995) notice the presence of a "value network", or a network of stakeholders that become aligned through the common understanding of performance dimension that is related to a particular product architecture. This suggests that technologies are situated in the common understanding of product performance and rely on the interpretation that stakeholders bring forward in specific contexts.

III. Effectual entrepreneurship

Entrepreneurship research describes the creation of business ventures as either a process of discovery or as process of creation of new business opportunities (Alvarez and Barney, 2007). Theories of opportunity creation view entrepreneurs as enacting the context they are immersed in, i.e., *effectual* entrepreneurship (Sarasvathy, 2008). According to this view, opportunities are built when entrepreneurs make use of their resources at hand (information, means, and partnerships) to achieve personal goals. Effectual entrepreneurship uses design to govern ventures locally and contingently, and by creating enduring systems that are near decomposable (Sarasvathy, 2003). Effectuation portrays market creation as a process where entrepreneurs control the design of the artefacts that compose the business venture.

The mechanics of market creation are explained as a collection of transactions shaped by the design of effectual contracts (Sarasvathy & Dew, 2005). In an effectual contract, the expert entrepreneur ideates and evaluates possible courses of action according to the means at hand. During the exploration of such options, entrepreneurs interact with possible stakeholders (suppliers, distributors, customers, etc.). An effectual contract appears when two stakeholders negotiate to commit means, in order to move the venture forward. Product architecture becomes central in the effectual contract since the design of the product is negotiated in order for the parts to work with it (Sarasvathy & Dew, 2005). Parallel to the mirroring process, Sarasvathy & Dew (2005) explain that the accumulation of these contracts expands the network of stakeholders that interact with the business venture, thus creating a market. Hence, Sarasvathy also highlights the importance of a common understanding in the semantics of the design of a market structure (Sarasvathy, 2004).

We propose to connect the study of product architecture and entrepreneurship. We also propose that this dual view of the innovation cycle provides a framework that links the design of a product architecture to the creation of markets. The rationale behind the articulation of technology cycles and entrepreneurship suggests that the complexity of a product's architecture is a salient factor that structures the negotiations between stakeholders in the creation of effectual contracts. Therefore, the design of a product's architecture represents the first step in the mirroring process between product architecture and market institutions.

IV. Product complexity

Suh (2005) defines complexity in design as the measure of uncertainty in achieving a functional requirement. The complexity in the implementation of a particular product architecture includes the definition of the functional requirements and the fabrication of the configuration (S. C.-Y. Lu & Suh, 2009). Inborn (or functional) complexity is built into the delineation of the artefact functions and thus is present in the original problem space of the design. Consequently, any artefact in the same category shares the same inborn complexity because it shares the same functional requirements. On the contrary, acquired complexity is the result of design decisions that balance the initial requirement with the available resources and manufacturing processes. Inborn system complexity has been the focus of most of product architecture studies (Browning, 2001; M. E. Sosa et al., 2004).

V. Method

We view entrepreneurial ideation as the conception of possible courses of action in the creation of new ventures. Research on entrepreneurial ideation focuses on social and cognitive perspectives that describe it as a problem solving device (Gemmell et al., 2012; Gundry et al., 2016). Yet, the theories of effectuation and mirroring suggest that this ideation mechanism relies on artefact exploration and interaction. Entrepreneurship mirroring suggests that within entrepreneurial ideation, the exploration of the product architecture informs the ideation of possible paths that the business venture can use to incorporate new stakeholders. Thus, product architecture informs the creation of the early connections between components that will get mirrored into the firm and the industry. We consider that entrepreneurial ideation interprets the product as part of the resources used to create possible opportunities for effectuation. Within the interpretation, the inborn complexity of the product structure is copied into the structure of the imagined courses of action; the number of elements and the interrelation between them. Therefore, the purpose of this study is to explore the effects of product complexity in the mirroring process within entrepreneurial ideation o confirm the link between product and organization structures in the beginning of the business venture. Based on the theories of architectural mirroring, we hypothesize the following:

> *H. The complexity of product architecture has a mirroring effect on the complexity of the results of entrepreneurial ideation.*

Business venturing is not exclusive to expert entrepreneurs or designers that have full knowledge of design processes and tools. Hence, the study focused the ideation process around mental imagery. The interaction between visual and mental representations is used in creative cognition research (Finke, 1996; Kudrowitz & Dippo, 2013). The exercise was designed as a survey that presented one of ten images of parametrically generated artefacts divided into five different categories of complexity and two categories of symmetry. The artefact images were distributed randomly through an online survey to 308 participants through Amazon MTurk (Cunningham et al., 2017). The instrument asked participants to mentally design a commercial application of the shape and complete statements about the product, the name and core values of the firm, its customers, and the involved stakeholders. As mentioned, there is no evidence that suggests that designers of product architecture in entrepreneurial ventures need to be expert designers (Davidsson, 2007; Gartner, 1988), therefore the participant selection criteria looked for people with interest in entrepreneurship, with an education degree of high school or higher, and between the ages of 18 to 64. These requirements are used by the Global Entrepreneurship Monitor to study entrepreneurial activity (Global Entrepreneurship Research Association, 2017).

VI. Survey design

i. Image input

Visual imagery has been used as a mechanism for generation and exploration of alternative solutions for creative tasks (Finke, 1996; Jankowska & Karwowski, 2015). Our survey used a generative design algorithm that created randomized configurations of rounded volumes with a desired number of components. The algorithm builds such components by creating an initial revolved body of randomized dimensions and drawing a grid of points in its circumference and transverse X and Y axes. It continues by selecting a random number of points as centres of for the creation of new bodies. The process repeats itself until the desired number of components is fulfilled. Five levels of complexity were selected, from two to six components, in order to create enough difference between the extreme stimuli, and at the same time avoid over-complicated images that became difficult to interpret. Symmetric and asymmetric images were introduced for variable control purposes (Figure 1).

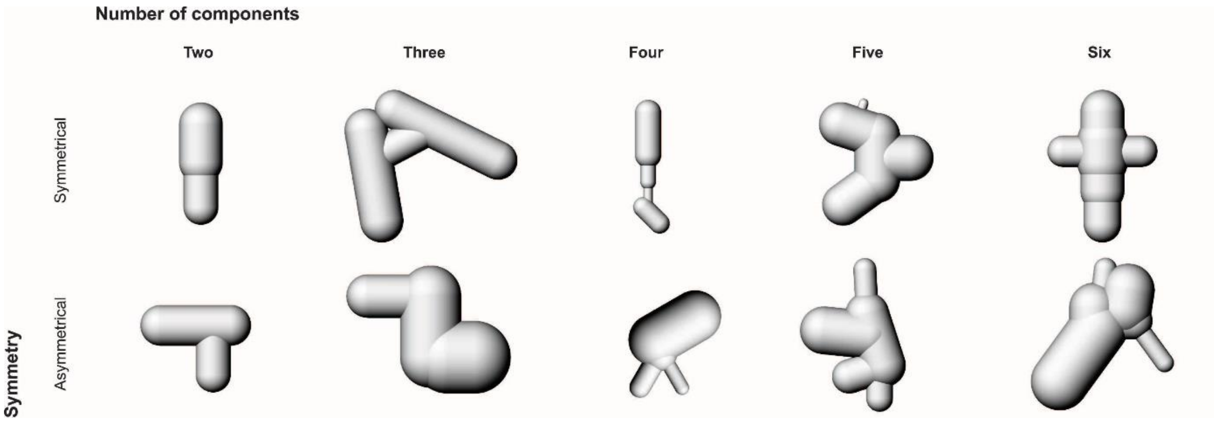

Figure 0.1. Collection of images used in the survey

Survey statements

The survey was composed by 13 statements to be completed by participants. Each statement was followed by a short instruction to aid completion. The statements focused on topics that concern business modelling.

1. The name of the product is (My product is a kind of (describe a category)...
2. describe a name)...
3. My product is designed to assist (describe the customer that will buy it)...
4. My product helps customers to (describe the goals of the costumer)...
5. My product fulfils these goals by (describe how the product works)...
6. My product competes against other products like (describe other product categories that could compete with your product)...
7. My product is better than its competitors because (describe the traits or qualities that make it the best option for your customers)...
8. The name of my brand is (describe a name)...
9. My brand is designed to reach (among your customers, describe the brand lead users/fans)...
10. My customers believe in (describe the values that your customers believe in)...
11. My brand partners with (describe categories of other firms you could partner with)...
12. Together with these partners we (describe the activities you could do with your partners)...
13. Therefore, my brand delivers our products through (describe your distribution channels or

how are your products delivered)...

Network evaluation and classification

Participant responses were portrayed as networks that showed the lexical semantic relationships between the words in the response. As a network system, its complexity can be compared to the complexity of the input product architecture. To confirm the hypothesis, more complex product architectures should entail more, or more interrelated lexical semantic relationships. These lexical semantic networks were recreated with a Natural Language Processing (NLP) algorithm (Bird et al., 2009a; NLTK Project, 2017). The algorithm searches each unique word within a pool of words in the WordNet database (Fellbaum, 2005) to find lexical-semantic connections. The search looked for relationships that included synonymy, antonymy, hypernymy, hyponymy, meronymy, metonymy, holonymy, homonymy and semantic entailments. The collection of connections was used to portray a network for each pool of words. Hence, each word pool was evaluated for the length of responses, the frequency of words, and the lexical depth of each word. Additionally, each corresponding network was measured for number of nodes, number of edges, number of nodes in contact with one or more words in the original text, and density of the network as complexity metrics. In order to optimize the classification with WordNet, the full text of answers was parsed and cleaned by removing stop-words, and functional words. Additionally, words that described character and actions that were not part of categorical descriptions were removed. The remaining words were grouped in pools for their analysis. With the objective of studying the effects of complexity at different scopes, the pools were assembled at four levels of aggregation: words in the same sentence (sentence), words in the same concept (concept), words originated in the same sentence for all the concepts regarding the same image (topic), and all words regarding an only image (image).

VII. Results

i. Survey participants

The survey ran for five days for workers who had at least received a High School degree. Participants were offered a compensation of $2.00 USD for their participation. A total of 308 responses were valid from 595 received. Invalid responses included incomplete answers, automatically filled with random characters, or words without sense (repetitions of the survey items or sentences made from the same word). All surveys were filled out in the United States. The average time for survey completion was 8:49 minutes. Participant profiles show a higher percentage of respondents with tertiary education and native English speakers (Table 1).

Table 0.1 Distribution of participants age, education level, and language

Age

	Frequency	Percent
18-24	26	8.4%
25-29	61	19.8%
30-34	54	17.5%
35-39	50	16.2%
40-45	32	10.4%
45-older	85	27.6%
Total	308	100.0%

Education degree

	Frequency	Percent
High School	36	11.7%
Diploma	56	18.2%
Bachelor Degree	134	43.5%
Postgraduate Diploma	6	1.9%
Postgraduate Degree	76	24.7%
Total	308	100.0%

Language

	Frequency	Percent
Native english speaker	303	98.4%
Foreign english speaker	6	1.9%
Total	308	100.0%

VIII. Concept content

Concepts were classified with the purpose of understanding a complete picture of the retrieved content. First, each concept was tagged with the most specific instantiation of object, personal identity, and organization identity mentioned by the participant. Second, each tag was related to any other tag that represented a superordinate or subordinate version of it. Next, a network of concepts was assembled by representing the relationships between tags with edges amongst the concept nodes. Finally, the network was divided in subsystems using a modularization algorithm (Blondel et al., 2008). The resulting network shows 10 modules that gathered concepts in semantic fields (Table 2). These semantic fields seem not to represent traditional superordinate categories of ideas, but themes that are more situational.

Table 0.2 Concept content distribution

Theme	Percent of Nodes
Games and Toys	22.73%
Gadgets and Electronics	18.51%
Massagers, Sports and Camping	12.34%
Pharmacy and Home Repairs	10.71%
Tools and Furniture	7.79%
Home Shopping Products	7.79%
Elderly Assistance	7.47%
Hand Graspable and Flexible	6.82%
Stress Balls and other Squeezeables	5.52%
A Chilly Pack for Injuries (stand alone idea)	0.32%

IX. Data Analysis

The different levels of aggregation evaluated 4,004 sentences, 308 concepts, 130 topics (13 per image), and 10 image word collections. Means differences in every metric were tested using a single ANOVA test for the number of components and symmetry variables in each level of aggregation. The results were counterintuitive since no significant differences were found in any metric at any aggregation level. No variation in any statistic was found to support complexity effects, thus rejecting the hypothesis. Moreover, within each examination, the relationship between the different component numbers did not present a pattern that could be associated with increasing numbers of components or symmetry. The relationships between statistics amongst the different numbers of components also differed from one level of aggregation to another.

Yet, in the comparison of the descriptive statistics between the different levels of aggregation, statistics for number of nodes, contact nodes, and density showed unexpected results. According to the properties of a growing network, the introduction of new nodes with new edges increases the number of possible connections between them. Thus, as density is measured with reference to possible connections between all the nodes in the network, the mean density of networks shows a decrement for every bigger aggregation level (Figure 2). Nevertheless, the number of contact nodes follows a different path and increments every time more words are incorporated despite the increment in node population (Figure 3). In a similar, unexpected fashion, the total number of evaluated nodes decreased from the sentence level with bigger levels of aggregation (Figure 4). A close examination of the data showed that the number of total evaluated words decreased, because same words in different sentences were considered as one by the NLP algorithm when all sentences were incorporated in a bigger pool. The repetition of words was an obvious reason that explained the reduction of evaluated words when transitioning from the sentence to the concept level where the same participant described the same concept. However, the repetition of words and the increased number of contact entailments in the topic and image levels suggested the presence of similar patterns in lexical-semantic relationships amongst participants.

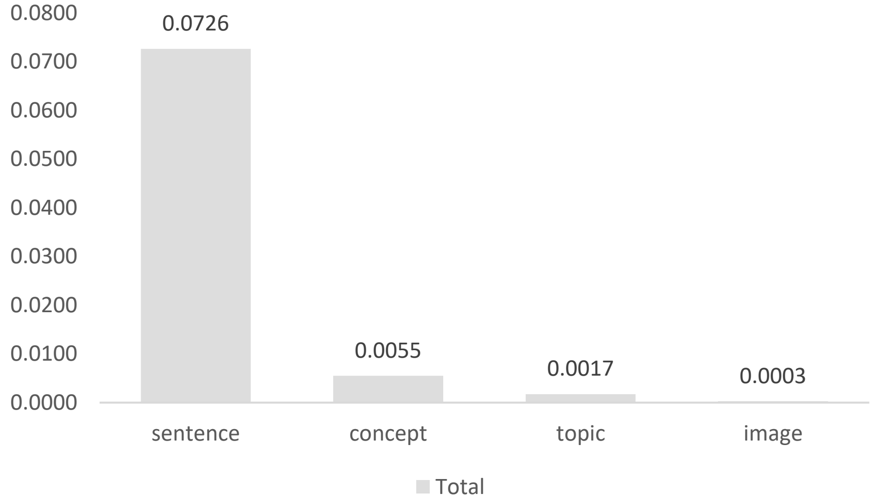

Figure 0.2 Mean density in networks at different levels of aggregation

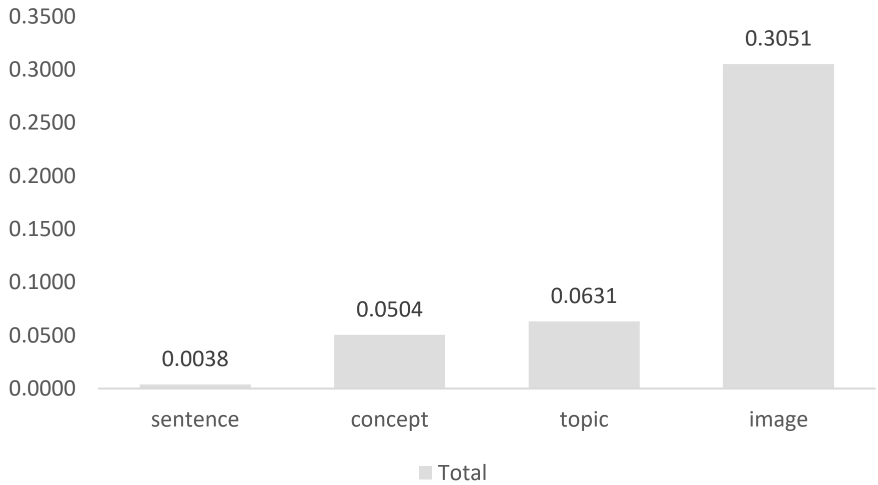

Figure 0.3 Mean contacts in networks at different levels of aggregation

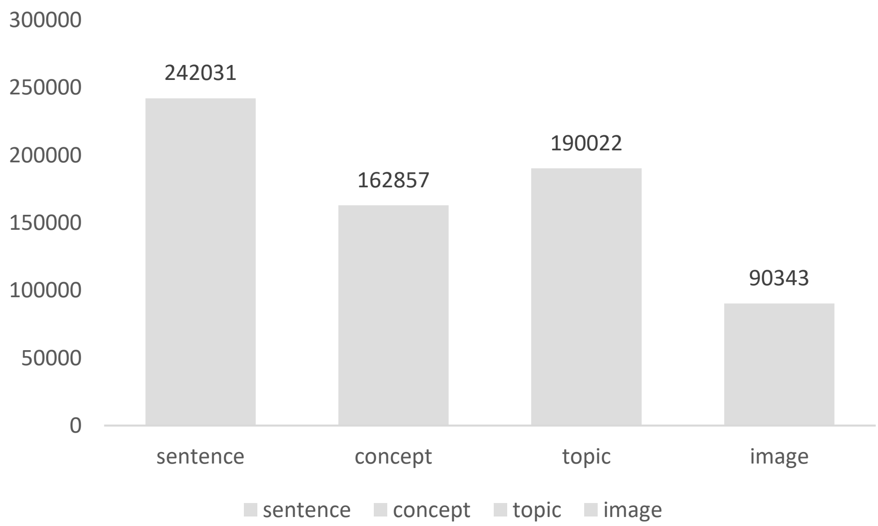

Figure 0.4 Total evaluated nodes at different levels of aggregation

A second analysis was undertaken with the purpose of looking at the repetition of words in bigger pools. The complete set of words from all responses was evaluated by using the same algorithm to generate a network that describes the complete universe of all the survey questions. Each word created a node that was tagged according to the number of images, themes, and questions that it was related to, the in-degree score, and closeness centrality in the network. Nodes were divided between original nodes in text and contact entailments between them. The network density and diameter were also evaluated.

The generated network contained 12,598 nodes, including both original (N = 2,218) and contact nodes (N = 10,380). A set of fitness chi-square tests were used to examine the distribution of these nodes amongst the number of manually coded themes they appeared in. A fitness examination with the themes would prove the presence of common interpretations. The tests show that original nodes are significantly distributed in any of these classifications. Two extremes of the distribution cluster most of the words, where 1,129 words (50.9%) are related to just one theme compared to 571 words (25.7%) that are shared in all themes. These distributions present strong effects from theme modularity (Cramer's V ≈ 0.5). On the contrary, contact nodes present an opposite concentration of 48 (0.4%) words that are related to a theme and mostly to one or two images. The other extreme is occupied by 6,464 contact words (62.3%) that are related to all themes and almost all questions and images. Again, the effects of this distribution are strong (Cramer's V ≈ 0.5).

In-degree scores were tested, since they indicate the concentration of relationships from other nodes in the network, contrary to out-degree that depends on the thesaurus definition of each word. ANOVA tests show that the extremes, in both original and contact nodes, that are in touch with more themes, concentrate a significantly higher in-degree of connections in the network ($\alpha \approx 0.0$). Therefore, in both original and contact nodes, words that are shared between groups also concentrate increased numbers of relationships.

X. Discussion

The results of this study lead us to re-examine the model of architectural mirroring that focuses on functional allocation and structural complexity. It is important to evaluate the influence of unaccounted variables in the experiment. For instance, individual differences can influence the generation of ideas based on personal backgrounds (e.g. participants 45 years and older that imagine products for children). However, the randomization of the survey platform, the topic level statistics and the fact that the shared vocabulary covers every image, discards this variable, at least as the most influential. Alternatively, another unaccounted variable that could explain such results is the morphology of the presented artefact. In spite of the intended "neutrality" in the design of the algorithm, the different images presented carry common visual properties (colour, texture, etc.). Neither in studies of architectural mirroring nor in mental imagery studies, have these features of design morphology been accounted for.

Secondly, the results prioritize the semantic dimension of product morphology instead of the structure of product architecture in the creation of new markets. The results show a semantic network that can be found within the concept of the value network (C. M. Christensen & Rosenbloom, 1995). Additionally, this semantic network can also be articulated with the model of the effectual contract (Sarasvathy & Dew, 2005) as the design space for the enactment of the product, and as a resource for the entrepreneur. Hence, artefact morphology can be considered an unaccounted externality, that shapes the available semantic relationships in the manipulation of a particular product or technology. This suggests that the creation of new markets entails a process of technological interaction, which can be translated as a process of "design as exploration", instead of "design as search"(Dorst & Cross, 2001). Therefore, we speculate here that architectural mirroring affects the perception of stakeholders as much as the morphology of the involved technology allows it to. Consequently, we propose the study of morphology as a filter or boundary of entrepreneurial ideation that happens before functional mirroring. Instead, product architecture and its mirroring might be determined within the boundaries already set by product morphology.

The unexpected quality of these results highlights the limitations of the study. We propose that a further examination of artefact morphology should be based on a wider semantic dataset that does not rely forcefully on the lexicon, as WordNet does. More specialized semantic databases could be assembled from the specific instances of business transactions such as early contracts, entrepreneurial pitch decks, product marketing, or landing pages. Similarly, the selection of the visual language has a great potential for operationalization and analysis. Altogether, this study questions the assumptions of complexity mirroring in the creation of new markets and the introduction of new products. At the same time, it creates an interface between design and entrepreneurship research that can articulate the effects of design morphology.

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