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Unveiling the dynamics between Frugal Innovation and Product Performance

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Index

Introduction

Frugal Innovation is approaching the current economic scenario as a substitute for the traditional, high-end view of doing innovation. In fact, it "seek[s] to create attractive value proposition for their targeted customer groups by focusing on core functionalities and thus minimizing the use of material and financial resources in the whole production process while fulfilling or even exceeding prescribed quality standards" (Tiwari, Fischer, and Kalogerakis, 2016:16). In other terms, it reconfigures existing product design reducing the non-essential features thus delivering the same value. The concept was born in low-income environments and rural area in response to the need of disadvantaged consumers, also defined the Bottom-of-Pyramid (Prahalad and Hart, 1999), gaining later the interest of Western firms which saw in these markets an opportunity to growth and to make profit. OECD estimated that by 2060 the 60% of world GDP will come from emerging markets (OECD, 2012). These markets are characterized by environmental and financial constraints as well as institutional voids, such as lack of infrastructures or access to water, health and credit system: for this reason, they are often referred as resource-constrained consumers.

The literature accounts for other terms related to frugal innovation. Among others, Low-end Innovation (Agnihotri, 2015), Bottom-of-Pyramid Innovation (Prahalad and Mashelkar, 2010), Bricolage Innovation (Baker and Nelson, 2005), Inclusive Innovation (George *et al.,* 2012; Heeks, Foster and Nugroho, 2014), reverse innovation (Govindarajan and Trimble, 2012). Despite having common elements, such as the idea that innovations should be low-cost, simple and yet useful, evidence from literature shows that these terms have not gained attention from academia and practitioners to the same extent as frugal innovation had (Bhatti et al., 2018).

As a novel field of research emerges, an assessment of the scholar discourse and the active communities in the field is required. The first chapter included in my thesis builds from this gap and provides a bibliometric analysis of the scientific domain in frugal innovation literature. The results unveil the presence of four research clusters focusing on different aspects of frugal innovation. These areas are related to low-end contexts, addressing sustainability issues, industrial applications and how western firms should adapt their strategy to engage in frugal innovation activities (whose different way to conceive innovation may requires adapting the organizational efforts). It emerges that a more decontextualized interest which focus on the "hard" aspect of innovation, i.e. product architecture, design, performance lacks from the current academic debate.

We build on this gap and we propose in the second chapter a theoretical model of product performance of alternative innovations approaches. To broaden the scope of frugal innovation and to remove the potential negative connection to the term 'frugal' we adopt the definition of 'alternative innovation' approaches. By testing the model through an agent-based simulation, we demonstrate that alternative approaches lead to an ultimate improvement of performance of the redesigned product. We aim to demonstrate that such approaches may constitute a valuable alternative to the 'conventional' innovation approaches.

The third chapter assume again a narrower perspective on frugal innovation adopting a product architecture perspective. In this chapter we propose a theoretical model, then tested through an agent-based simulation, which analyzes frugal innovation approach as product architecture innovation and the factors determining a stable achievement of improved product performance. Following Lim and Fujimoto (2019), we advance the idea that frugal innovation approaches span much broader boundaries than what recent literature proposes. The existence of a consumer's segment interested in "less fancy" characteristics, preferring a more low-cost version of the products and willing to forgo fancy and high-end technological characteristics, or consumers affected by the "overengineered syndrome" (Herbig and Cramer, 1992), would be a driver for firm growing interest in frugal innovation.

This thesis adopts a multidimensional perspective of frugal innovation: after reviewing the literature, it attempts to provide a different framework to understand the frugal innovation phenomena, especially from a product design perspective, contributing to the literature of frugal innovation and, to lower extent, to the literature of product innovation and product architecture.

Chapter 1: A Bibliometric map of Intellectual Communities in Frugal Innovation Literature

Abstract

Frugal Innovation (FI) is the process of innovating to respond to severe resource constraints with products that have cost advantages compared to existing solutions; the philosophy behind frugal innovation can be applied to both products and services from different sectors, as showed by academia and managerial applications. The purpose of this paper is to examine the intellectual structure of the developing research domain of frugal innovation in order to identify the most active and influential communities, as well as the most seminal works and scholars that are active in the field. Therefore, we conducted a bibliometric analysis of the literature of Frugal Innovation: the outcomes of our analysis allow us to offer an objective and scientific mapping of the development of this field.

Four distinct intellectual communities have been identified: Strategic Challenges; Inclusive Development; Sustainability and Industrial Application. We provide insights into the commonalities between these distinct communities and the intellectual structure of the domain, as well as indications for future studies. Moreover, the results highlight issues related to the development of frugal innovation, for managers as well as for policy makers.

KEYWORDS: Frugal Innovation, Bibliometric analysis, Intellectual community, Research Collaboration, Scientific Mapping

Introduction

The concept of Frugal Innovation (FI) dates back to 2006, when the Renault-Nissan CEO Carlos Ghosn coined the term "frugal engineering", inspired by the Indian engineers' ability to innovate "cost-effectively and quickly under severe resource constraints" (Radjou, 2012). A few years later, the term appeared in an article of The Economist (The Economist, 2009) which introduced the idea of a frugal approach to innovation in the Indian healthcare system. In the article, the logic of frugal innovation was explained as follows: "unlike the hidebound health systems of the rich world, in a patient-centric health system you must innovate. This does not mean adopting every fancy new piece of equipment. Over the years he [interviewed doctor] has rejected surgical robots and 'keyhole surgery' kit because the costs did not justify the benefits. Instead, he has looked for tools and techniques that spare resources and improve outcomes" (The Economist, 2009).

Frugal innovation has been defined as designing low-cost products, systems and services by removing sophisticated technology without losing technical functionalities, and thus make them affordable for low-income customers, either in low-, middle- or high-income countries (van Beers, Knorriga and Leliveld, 2012). One of the most prominent example is the GE portable diagnostic ultrasound machine, developed for China's rural areas (Immelt, Govindarajan and Trimble, 2009; Govindarajan and Ramamurti, 2011), and based on an old, low-cost ultrasound technology device that can be connected to any laptop. It differs from its 'traditional' counterpart for its ease of use (with a simplified user interface), lower price (80% lower than the conventional ones), portability and battery endurance.

The frugal innovation approach is increasingly becoming popular among companies as a different way to innovate and design creative and innovative solutions (Immelt, Govindarajan and Trimble, 2009; Radjou, 2012). This is clearly attractive to companies thanks to beneficial and appealing consequences such as squeezing costs, enlarging the consumer base, and exploiting existing resources. Another reason behind the appeal of the topic relates to a major change in consumer's behavior, which is arguably moving from "ever-bigger and better" solutions towards a growing demand for the reduction "in the needless complexity layered on the technology-based products" (Hanna, 2012). This trend is furthermore reflected in the phenomenon of "innovation overload" (Herbig and Kramer, 1992), defined as a consumer's response to the increasing pace of innovations, information and knowledge: in other words, it refers to the fact that consumers are suffering from the so-called 'over-engineering syndrome', they are no longer willing to pay for features they perceive as not valuable, and might be interested in simpler but still valuable products.

Although frugal innovation was born and developed in the practitioner context (Radjou, 2012), it has also captured an increasing interest of the academia. After a few years of "incubation", various scholars have been attracted by the novelty of the topic, and frugal innovation has become an academic field of research. In the academic sphere, the major scholars debate the overlap of frugal innovation with multiple similar terms, such as *jugaad*, frugal engineering, constraint-based innovation, Gandhian innovation, catalytic innovation, grassroots innovation, indigenous innovation, and reverse innovation (Brem and Wolfram, 2014). In fact, other terms describing similar concepts have become popular among practitioners and scholars, which make the boundaries of frugal innovation blurred.

It is thus hardly surprising that previous research on Frugal Innovation has included systematic literature reviews for several reasons: to define the differences between frugal innovation and related (Brem and Wolfram, 2014; Marco Zeschky, Winterhalter and Gassmann, 2014; Agarwal *et al.*, 2017), to provide a definition of the concept (Soni and Krishnan, 2014; Weyrauch and Herstatt, 2017; Pisoni, Michelini and Martignoni, 2018), to summarize the key findings of researches (Hossain, 2018; Pisoni, Michelini and Martignoni, 2018) and to map the scientific domain (Nair *et al.*, 2015; Agarwal *et al.*, 2017). Although systematic literature reviews allow to assess the state of a research domain, it encompasses weaknesses which may skew the results: the need to find a metric to evaluate and summarize the findings may miss out relevant contributions, and the non-replicability of the analysis due to the qualitative dimension of the systematic literature reviews, as researchers may report only the literature which is relevant and consistent with their bias.

The purpose of the paper is to examine and classify the literature on frugal innovation relying on a quantitative approach, in order to provide a deeper understanding of the current state of the research and to outline directions for future research. To overcome the aforementioned limitations, we conduct a bibliometric analysis of the literature: notably, bibliometrics is a quantitative method to conduct a literature review which combines the classification and visualization methods of analysis of aggregated bibliographic data produced by scientists of a research domain (Galvagno, 2017). Our dataset consists of 67 articles covering the period 1985-2018, obtained from the ISI Web of Science SSCI database (which includes impact factor journals and refers only to business and management) as the data source, through the search by topic using the keyword "frugal innovation".

We uncovered the presence of four communities of scholars active in the field, as well as the strength of their connections and similarities between their different contributions. Our analysis provides a scientific mapping of the research domain based on the similarity between each piece of research. Our contribution to the literature of frugal innovation is twofold: first, we unveil the sub-areas of the research domain and the key insights offered by the pertaining scholars; second, we discover potential weaknesses of the current research, suggesting how future research may address those gaps.

The article is organized as follows: in the next section, we "review the reviews" of frugal innovation. The third section explains the bibliometric approach and the methodology. The fourth section presents and discusses the results. The final section provides the conclusions and suggestions for future research and the limitations of the study.

Overview of the Literature

Over the past years, different authors have contributed to defining and reviewing the frugal innovation field of research, as summarized in Table 1.

Brem and Wolfram (Brem and Wolfram, 2014) included frugal innovation in the more general category of innovation for emerging markets. Similarly, Zeschky et al. (Marco Zeschky, Winterhalter and Gassmann, 2014) clustered the innovation approaches for emerging markets in three groups according to the attributes of market novelty and technical novelty, with frugal innovation being one of the three clusters together with cost-innovation and good-enough innovation. Agarwal et al. (Agarwal *et al.*, 2017) focused on innovation under scarcity, synthetizing the extant research to organize the fragmented literature and terminology confusion. Although their systematic literature review identified the progress of extant research and future directions providing a clusterization of the extant research domain, it included frugal innovation and other terms under the umbrella of resource-constrained innovation. Therefore, the results span much broader boundaries and do not provide helpful insights about the frugal innovation domain. Hossain (Hossain, 2018) addressed the gap providing a map of the frugal innovation phenomenon based on the country of origin of the research and the journal of publishing. Later on, Pisoni et al. (Pisoni, Michelini and Martignoni, 2018) assessed and reviewed the key findings of frugal innovation literature through an in-depth systematic literature review. Based on qualitative content analysis, they provided multiple classifications of the contributions based on different metrics, thus resulting in a very complete framework of the research which, however, may also be overly elaborate and difficult to summarize.

Although the previous studies offer a comprehensive overview of the existing terms and offer various keys to draw the boundaries between the terms, a quantitative analysis of the overall state of the art in frugal innovation literature is still lacking.

Authors	**References**	**Metrics**	**Purpose**	**Methodology**
Brem and Wolfram	(Brem and Wolfram, 2014)	Innovations for emerging markets	Review of the literature	Literature Review
Zeschky et al.	(Marco Zeschky, Winterhalter and Gassmann, 2014)	Innovation under constraints	Identify criteria to classify innovation for emerging markets	Theoretical Paper
Agarwal et al.	(Agarwal *et al.*, 2017)	Innovation under constraints	Review and Organize the	Systematic Literature

			literature and the terminology	Review and Cluster Analysis
Hossain	(Hossain, 2017)	Frugal Innovation literature	Mapping frugal innovation	Systematic Literature Review
Soni and Krishnan	(Soni and Krishnan, 2014)	Definition of frugal innovation	Definition of frugal innovation	Systematic Literature Review
Weyrauch and Herstatt	(Weyrauch and Herstatt, 2017)	Definition of frugal innovation	Definition of frugal innovation	Literature Review, Interview
Pisoni et al.	(Pisoni, Michelini and Martignoni, 2018)	Frugal innovation literature	SLR Frugal Innovation literature	Summarize the key findings

Table 1: Overview of the previous literature reviews

Methodology

We conducted a bibliometric analysis to construct a scientific map of the scientific domain of frugal innovation. Bibliometric analysis is a quantitative methodology that analyzes bibliographic data to identify the strongest interconnections among articles and research topics analyzing citation relations, co-citation relations, and co-occurrence of the keywords (Solomon, 2015). It enriches the findings of the traditional methods of review studies, notably the qualitative approach of the systematic literature review and the quantitative approach of meta-analysis (Schmidt, 2008; Zupic and Čater, 2015). In fact it combines an initial, quantitative analysis and a second, subjective analysis of the results through coding procedures, providing a more complete understanding about how the authors and papers are related to one another and then producing visual representations (Tranfield, Denyer and Smart, 2003; Zupic and Čater, 2015). It is based on the assumption that any scientific area results from a cumulative research tradition occurring over time, which can be captured through a pattern of citations (Ardito *et al.*, 2018). By analyzing these patterns of citations, is it possible to scrutinize relationships among documents contributing to the development of a research area (Di Stefano, Peteraf and Verona, 2010).

Analytical Approach

The unit of analysis is constituted by the single article. In line with previous scholars (van der Have and Rubalcaba, 2016) we relied on bibliographic-coupling strength to detect scholar research communities (Kessler, 1963; Boyack and Klavans, 2010). The bibliographic-coupling strength (or frequency) between two documents is defined as the number of items these two documents share in their reference lists. Two documents are bibliographically coupled if they both cite one or more documents in common; the higher the number of documents cited by the two documents, the higher the bibliographic-coupling strength. The rationale behind the measure is that the documents that share the same references are likely to be similar, and this similarity is higher as the shared bibliography increases. We choose the bibliographic coupling as similarity measure to map the scientific domain (Kessler, 1963), as it has been recognized by the literature as the most accurate for representing a research front (Boyack and Klavans, 2010), as it is not affected by the cumulative amount of a citation like other similarity measure (Glänzel and Czerwon, 1996). In the past years the accuracy of the bibliographic-coupling measure to study the academic fields has been compared to another method of analysis of scientific publications, the co-citation technique (the frequency with which two documents are cited together (Small, 1973)): the object of the comparison was the goodness of each method to cluster the academic fields of research, also if the literature on bibliometrics agrees on the superior accuracy of bibliographic-coupling techniques as compared to co-citation techniques (Peters, Braam and van Raan, 1995; Jarneving, 2007b, 2007a; Boyack and Klavans, 2010).

Bibliographic coupling strength assumes that papers sharing the same references are similar, and the higher the amount of shared references, the higher the similarity. In this view the bibliographic-coupling analysis applied on the references allows the identification of the main clusters of scholars working on sub-topics (through the similarity analysis). Afterwards the clusterization conducted by a VOSviewer software, a content analysis of the results obtained was performed, and each cluster has been manually screened and labelled through a coding procedure (Strauss and Corbin, 1998). The VOSviewer software (version 11.4) generates maps (Van Eck and

Waltman, 2007) using the VOS mapping and VOS clustering techniques (Waltman, van Eck and Noyons, 2010). These are novel, alternative techniques to the Multidimensional Scaling (MDS) approach (Appio, Cesaroni and Di Minin, 2014), to some extent resembling it as they both locate items in a low-dimensional space in such a way that the distance between any two items reflects the similarity or relatedness of the items as accurately as possible (Appio, Cesaroni and Di Minin, 2014). However, in contrast to MDS, which is based on the calculation of similarity measures like the cosine and the Jaccard indexes, VOS adopts a different procedure for normalizing co-occurrence frequencies (Van Eck *et al.*, 2006; Van Eck and Waltman, 2007), namely, the association strength (1). Specifically, the association strength is calculated as follows:

$$a_{ij} = \frac{mc_{ij}}{c_{ii}c_{jj}}, \qquad (1)$$

with *m* representing the total number of abstract, c_{ij} indicating the number of abstract where concept *i* and concept *j* occur together, and c_{ii} and c_{jj} indicating the number of abstracts in which respectively concept *i* and concept *j* occur. To compute the similarity of two documents, a two-step approach is taken. In the first step, for any pair of items, the number of bibliographic coupling links is calculated. In the second step, the association strength formula is used to normalize the bibliographic coupling strengths. The normalization corrects for the fact that some items (e.g., some documents, authors, or journals) may have many more references than others and may therefore also have more bibliographic coupling links.

Data

We collect our dataset from the Social Science Citation Index (SSCI) at the ISI Web of Science Core Collection[1]. Selecting the SSCI we ensure that we are filtering out any bibliographic data from less reputable journals and we are obtaining a dataset made of the articles published in the best peer-reviewed journals in the social science. As frugal innovation is a recent phenomenon, we

[1] Our results refer to papers available in the Web of Science database at October 2018

have not imposed any date restriction for the search. The dataset was obtained by running a "search by topic" with the keyword "frugal innovation", resulting in 67 articles (56 articles, 7 reviews and 4 editorial materials). We screened the dataset to filter out any incompatible articles, resulting in a final dataset consisting of 65 units in total. Although the literature has reported differences between the concept of Frugal Innovation and its established synonyms (Gandhian Innovation, Jugaad, Frugal Engineering) (Agarwal *et al.*, 2017), there are still some taxonomical issues which may alter our results. To account for this potential distortion, we verified the gap between our sample (keyword 'frugal innovation') and the samples obtained with the other terms (Gandhian Innovation, Jugaad, Frugal Engineering). The results show an overlapping of 45% with the keyword 'jugaad', 33% with the keyword 'Gandhian Innovation' and 18% with the keyword 'Frugal Engineering'.

Results

Frugal innovation as an emerging field

The analysis of the descriptive statistics provides a first understanding of the research field. The Figure 1 shows that the first academic publication appeared in 2011. In addition, the observation period can be divided into two different phases: an initial phase of less intense activity from 2011 to 2014, with four average publications per year, and a "take-off phase" between 2015 and 2018 (which is the most prolific year with 21 publications).

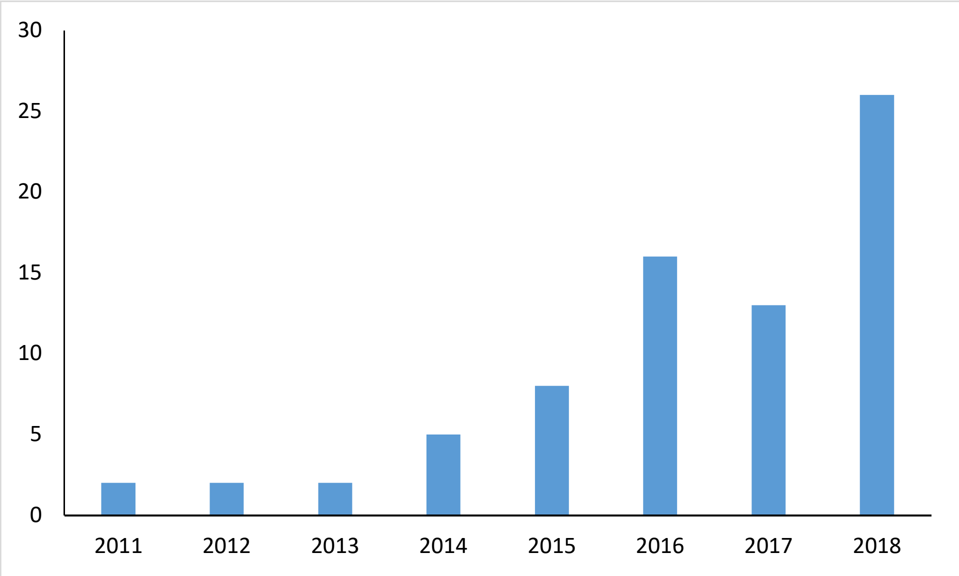

Figure 1: Total publications by year

The cumulative citations observed over the years see a significant increase during the take-off phase, with a peak of 191 citations in 2018, as shown in Figure 2 and a total number of citations of 519 over the entire period.

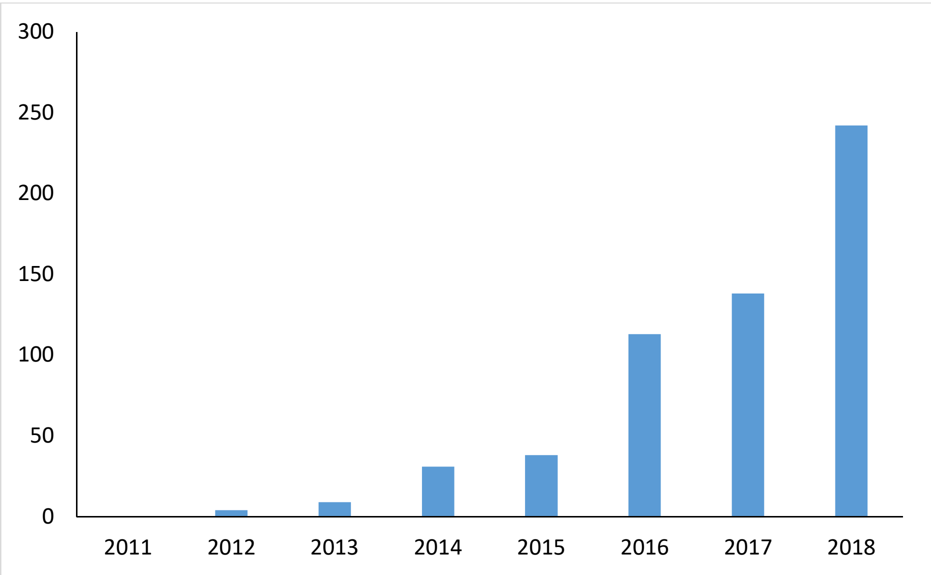

Figure 2: Sum of times cited by year

The geographical dispersion of the publications shows that the most prolific country is the US, followed not surprisingly by India, and Germany.

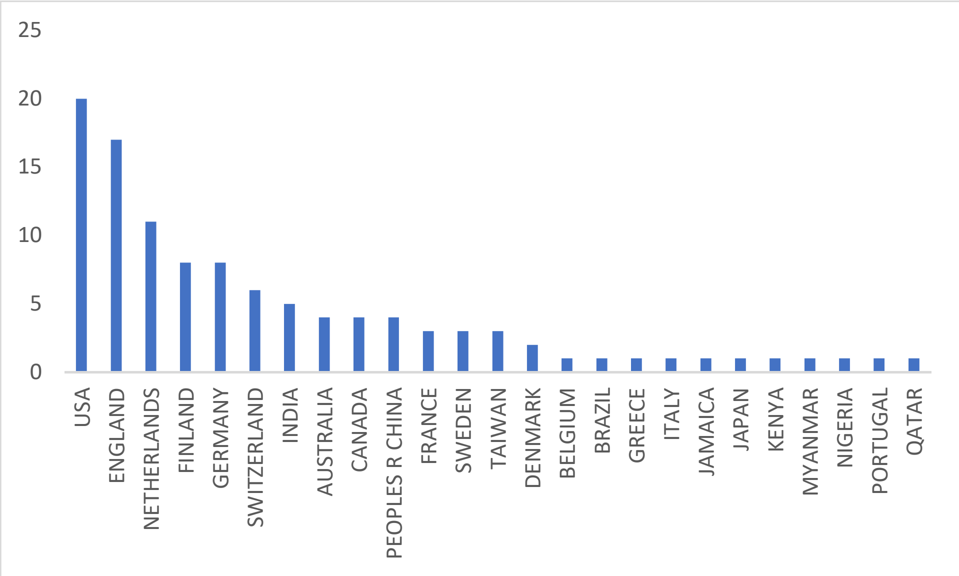

Figure 3: Citation map of the literature on Frugal Innovation

Scholarly communities

Following van der Have and Rubalcaba (2016), we created a network of scientific article on frugal innovation based on bibliographic coupling data (Kessler, 1963), as displayed in Figure 4. Papers are bibliographically coupled when different authors cite one or more papers in common. In other words, if two or more authors cite the same article, the authors are connected. The higher the number of citations they share with other documents, the higher the strength of the similarities

Figure 4 reports our bibliographic coupling map, covering 59 items out of 66 in total, i.e. 92% of the entire dataset. The bibliographic coupling map provides a visual representation of the network of papers belonging to a research domain, where each node represents a scientific paper and each tie represents a bibliographic coupling relation; the size of the nodes represents the number of citations the paper has received over time, while the distance between nodes represents the similarity between the nodes (measured by bibliographic coupling). The colors of the nodes represent different clusters of papers. The bibliographic coupling map shows 59 out of 66 total articles of the initial dataset; since the seven remaining papers were not connected with any others and therefore have been dropped from the map.

The papers that are not connected do not share any common citations with other papers in the dataset. A deeper analysis of the abstracts of those papers explain why they are disconnected from the map: those papers are scientific works about sophisticated technical applications of frugal innovations to surgery procedures (O'Hara, 2015; Bloem *et al.*, 2017), or technical applications of frugal innovation to solar energy (Nocera, 2012), and they apparently belong to different fields of research and refer to different literature bodies. The final network is made up by four main clusters, and after an analysis of the single title and abstract within, we came to the following cluster labels based on their main content: 1) Strategic challenges (Green); 2) Inclusive Development (Blue); 3) Sustainability (Yellow); and 4) Industrial Application (Red). The Table 2 summarizes the results and the key findings of the cluster analysis.

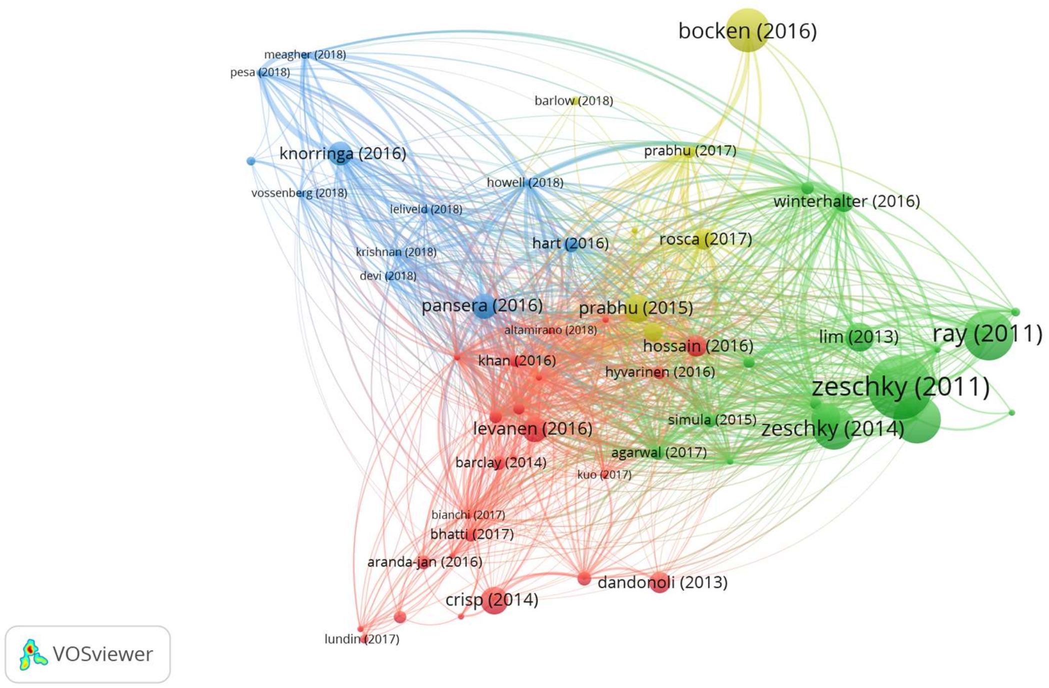

Figure 4: Bibliographic coupling map

Green Cluster (Cluster 1): Strategic Challenges

The green cluster comprises the most cited papers, as shown by the size of the nodes, thus implicating a potential dominant position of the cluster over the others in terms of popularity of the research focus. The analysis shows that the cluster addresses the strategic challenges of frugal innovation in terms of how organizational structures interplay with frugal innovation (Zeschky, Widenmayer and Gassmann, 2014; Altmann and Engberg, 2016), and the new product development strategies to meet the requirements of frugal innovation (Zeschky, WinterhalterProf and Gassmann, 2014; Winterhalter, Zeschky and Gassmann, 2016; Winterhalter *et al.*, 2017; Pandit *et al.*, 2018), and the new product development strategies to meet the requirements of frugal innovation (Ray and Ray, 2011; Sharma and Iyer, 2012; Gupta *et al.*, 2018). The main rationale for the community is that both for western firms and emerging market firms, a frugal innovation activity requires reconsidering the philosophy behind the traditional innovation strategy and to adopt a different view and mindset, in order to configure the value chain and to adapt the organizational structure to guide the new challenge. Besides the attention to the strategic and organizational themes and possible recipes for companies to tackle frugal innovation strategies, a sub-group of authors addressing the 'frugal' product development strategy emerges (Ray and Ray, 2010; Altmann and Engberg, 2016; Gupta *et al.*, 2018). These authors cross the external layer of the strategic challenges themes and seek to "get their hands dirty" with more technical issues. Indeed, they observe the phenomenon from a product performance perspective exploring the product architecture implications of frugal innovation in terms of product design. This sub-area, although immature, constitutes a promising avenue for future research, as it may disentangle the relation between frugal innovation and product design and provide findings about the performance of frugal innovation products, which in turn may encourage companies to embrace frugal innovation strategies.

Blue Cluster (Cluster 2): Inclusiveness

The second cluster deals with the theme of inclusiveness promoted by frugal innovation. Scholars focus on how frugal innovation can pursue social goals of reducing poverty and inequalities and promoting an improvement of the quality of life ensuring employment and providing adequate public services delivery in remote rural areas (Baud, 2016; Hart, Sharma and Halme, 2016; Howell, van Beers and Doorn, 2018; Krishnan and Foster, 2018; Leliveld and Knorringa, 2018; Peša, 2018; Vossenberg, 2018). The research community is characterized by two folded trends: the specificity of the setting of their studies, which are mainly contextualized in Africa (Howell, van Beers and Doorn, 2018; Krishnan and Foster, 2018; Leliveld and Knorringa, 2018; Meagher, 2018; Peša, 2018) and, in line with the topic of the cluster, in emerging markets as a whole (Devi and Kumar, 2018); the idea that frugal innovation for inclusiveness is a matter of global politics and development economics and would be better addressed from a macroeconomic perspective (Baud, 2016; Krishnan and Foster, 2018; Leliveld and Knorringa, 2018; Meagher, 2018; Peša, 2018; Vossenberg, 2018). In fact, the role of local institutional environment and the local governments are crucial to promote frugal innovation model. As such, a global policies perspective could address the issue by prompting the participation of western incubators and firm's facilitators as well as NGOs and western funds to provide both financial support and the transfer of technical knowledge (Chesbrough *et al.*, 2006; Banks and Hulme, 2012). These ingredients are determinant to avoid small, localized and grassroot private initiatives that would not survive to the market effects.

A further issue which is properly addressed by the literature is the threats of potential socio-economic inequalities driven by the diffusion of frugal innovation models (Leliveld and Knorringa, 2018; Peša, 2018) or the increase of capitalist exploitation and inequality (Schwittay, 2011). Future research is encouraged to address these issues, finding new solutions that can enable "win-win" situations, in which companies can earn profits while alleviating poverty, and ensure equal possibilities for the whole population of potential consumers (Leliveld and Knorringa, 2018).

A potential response to address the challenges posed by income inequalities could be solved by intertwining the impact of frugal innovation to address inclusiveness with the idea of democracy as an innovation enabler (Campbell and Campbell, 2019). In this respect, the political system is a critical factor which can serve as an innovation incubator under certain conditions, which is above all a "highly qualified" democracy. Indeed, a functioning democracy is arguably a prerequisite for the development and adoption of an effective innovation system, promoting an extensive coverage and ensuring social welfare.

The current literature considers frugal innovation as an essential ingredient for an onwards development trajectory of the low-income areas of the world, assuming that there is only one possible development trajectory where the whole society aspires. This is true because people from lower segments of the social pyramid seeks for a lifestyle improvement close to the western consumers (Prahalad, 2005).

Yellow Cluster (Cluster 3): Sustainability

The yellow cluster is the "less popular" of the research domains with only seven items, thus revealing a limited interest of practitioners towards the themes of sustainability and environment. The papers focus on how innovating under resource scarcity principles and reduction of non-essential characteristics may address environmental- and resource consumption issues (Prabhu, 2017), (Rosca, Reedy and Bendul, 2018), (Bocken and Short, 2016). The idea that frugal innovation has the potential to achieve sustainable development goals reconciles the community of scholars of cluster 3: in fact, they all agree on the latent capability of frugal innovation to tackle pressing sustainability issues thanks to its default attributes of less resources and optimized performance (Weyrauch and Herstatt, 2017).

In this respect, frugal innovation blends with the broader literature of sustainability issues and commitment toward the environment as part of the Sustainable Development Goals promoted by the United Nations (UN, 2015). Accordingly, frugal innovation enables us to simultaneously address the goals of "eradicating poverty", "to protect the planet from degradation, including through sustainable consumption and production" and to "ensure that all human beings can fulfil their potential in dignity and equality and in a healthy environment" thanks to its applicability also in disadvantaged settings. Given the growing interest of sustainability themes, we encourage research in frugal innovation to address these issues, providing empirical investigation of the ability of frugal innovation to fulfill multiple goals at the same time.

Red Cluster (Cluster 4): Industrial applications

The red cluster comprises the industrial applications of frugal innovation and is accounted to be the largest cluster with its 24 articles. This community is characterized by the presence of a small group of scholars from Industrial Engineering and Environmental Science, working on the industrial applications of frugal innovation.

A first level of analysis shows that the contents of the articles are diverse and span across different case studies analyzing various applications of frugal innovation; popular applications appear to be in the water supply system (Hyvärinen, Keskinen and Varis, 2016; Levänen *et al.*, 2016) and energy sector (Levänen *et al.*, 2016); the Indian mobile phone industry (Rai, 2015), the supply chain (Shibin *et al.*, 2018) and the general applications of frugal innovation to foster green technologies (Pansera and Sarkar, 2016; Kuo, 2017). However, the most popular application among scholars appears to be the healthcare sector (Dandonoli, 2013; Crisp, 2014; Aranda-Jan, Jagtap and Moultrie, 2016; Bhatti *et al.*, 2018), possibly to honor the tradition of frugal innovation born in the healthcare setting ('Lessons from a frugal innovator', 2009).

A deeper analysis shows that some of the articles belonging to the cluster 4 could be included in other clusters: for example, the industrial application of frugal innovations encompasses also themes related to product development issues (cluster 1), although cluster 4 focus on process rather than product design. The theme of frugal innovation applied to industrial process and utilities suffer from a narrow focus on application in low-income settings and emerging economies (Rai, 2015; Hyvärinen, Keskinen and Varis, 2016; Pansera and Sarkar, 2016; Agarwal, Brem and Grottke, 2018), which hinders a more comprehensive view of the effects of the application of frugal innovation to the industrial systems of more advanced economies. Future research should address the issue by providing the missing link between frugal innovation and industrial process application in the advanced economies; in addition, future research is encouraged to concentrate more on frugal innovation process and product development, in view of a possible increased adoption of frugal innovation practices and to equip practitioner with a “user manual”. In addition, future research may investigate the relation between industrial applications and patent activity issues, for example how much of frugal innovations turns into patent applications and granted patents, or which are the technological fields with the highest patent application rate. To the best of our knowledge, little attention has been devoted to the analysis of the frugal innovation production analyzing the patent activities (Howell, van Beers and Doorn, 2018; Krishnan and Prashantham, 2019). The promises of eventual future revenues from frugal innovation patenting activities could encourage innovation efforts in such direction, resulting in advantages for both companies as innovation-generator and society.

Sensitivity Analysis

The resolution parameter γ of the clusters determines the level of detail provided by the software's technique; the larger the value of the parameter, the larger the number of clusters that will be obtained and the smaller the clusters. We set a resolution parameter of 0.75, resulting in four clusters. Following Waltman et al. (2010) we experimented several different values for the resolution parameter. Accordingly, there is no generally optimum value of γ, and it should be based on the most purposeful results for the specific needs; in addition, the exploratory nature of the analysis makes justify the testing of different values. After some experimenting, we decided to set this parameter equal to 0.75. This turned out to result in a clusterization with a satisfactory level of detail for the purpose of our research - to detect the most influential communities of the research field. Indeed, a higher resolution parameter will result in a higher number of clusters on the one hand, with a higher level of detail and a more accurate detection of the content of the clusters, but on the other hand it will be pointless for the purpose of this specific research, resulting in a multitude of small clusters.

To assess the goodness of the resolution parameter, we conducted a sensitivity analysis to determine how the change of the parameter would affect the change of the results. By setting a resolution parameter γ=0.5, the clusterization algorithm detects two clusters:

- Cluster 1*: Industrial Applications, Inclusiveness and Sustainability
- Cluster 2*: Strategic Implication of Frugal Innovation/Creating Value with Frugal Innovation

Cluster 1* groups Cluster 2, Cluster 3 and Cluster 4, including the works that focus on the case studies of frugal innovation and how this approach can address social purposes. Cluster 2* reflects the Cluster 1 of the main analysis, addressing the strategic challenges posed by the adoption of frugal innovation strategies and how this approach can contribute to value creation, showing that a lower resolution parameter results in a merging of the clusters identified in the main analysis in two macro-categories.

By setting a resolution parameter γ=1, the resulting network shows six clusters:

- Cluster 1^: Case studies and Applications
- Cluster 2^: Inclusiveness and Social Development
- Cluster 3^: Strategic Implications
- Cluster 4^: Sustainability
- Cluster 5^: Development of Frugal Innovation Capabilities
- Cluster 6^: Applications in Utilities Sector

The higher resolution parameter results in a higher number of clusters. A deeper analysis shows that a higher parameter leads to the decomposition of the clusters identified in the main analysis: Cluster 1^ and Cluster 6^ are sub-units of Cluster 3, Cluster 2^ overlaps with Cluster 2, Cluster 3^ and Cluster 5^ are sub-units of Cluster 1, and finally Cluster 4^ overlaps with Cluster 4 of the main analysis.

The results of the sensitivity analysis show how, by setting a higher or lower resolution parameter, the clustering configurations result in macro groups in the case of lower resolution parameters, and sub-groups in the case of higher resolution parameter, confirming the goodness of the resolution parameter selected for the analysis.

Popular Theoretical Lenses

The qualitative analysis of the clusters shows the most recurring theoretical lens to observe the phenomenon: Disruptive Innovation and Bottom-of-Pyramid.

Disruptive Innovation (Christensen and Bower, 1996) describes a situation where existing companies are focused on satisfying the needs of the high-end of the market (where the profitability is high), ignoring the low-end of the market, which demands for less sophisticated and less performing products. In such situations new firms can enter the market serving the low-end consumers with lower expectations and requirements. As these innovations improve over time, they overtake the existing technologies, by satisfying current market needs (Cockram, 2017). The metrics of disruptive innovation show many common features with frugal innovation, e.g. the unserved consumer group or low-income markets, which are potential targets for frugal innovations (Ray and Ray, 2010; Khan, 2016), and the features of disruptive innovations which are typically simpler, more convenient and more affordable (Smith, 2003). Similarly, there is no empirical evidence of frugal innovations that have displaced their "traditional version", leaving the argument on a theoretical level. Disruption is a process and not an event (Christensen, 2006) and the evolution of the healthcare industry in developed markets and other factors will most certainly play a role in this disruption process. The papers which have relied on disruptive innovation to observe the frugal innovation phenomenon (Ray and Ray, 2011; Marco Zeschky, Winterhalter and Gassmann, 2014; Harris *et al.*, 2016; Shan and Khan, 2016; Pandit *et al.*, 2018) belong, not surprisingly, to the Strategic challenge cluster. This cluster's researchers aim to disentangle all the possible strategic challenges that firms dealing with frugal innovation may encounter, as the potential disruptiveness of frugal innovation may be significant. In addition, they contribute to address the bridge between frugal innovation and disruptive innovation, broadening the spectrum of what can result as disruptive for existing incumbents and what threats existing companies may face from "unsuspected" entities. In accordance with these authors, we believe that the lens of disruptive innovation may offer a fruitful theoretical dimension to the phenomenon.

The second theoretical perspective assumes a demand-based view and looks at frugal innovation from the potential targeted market side. The characteristics of frugal innovation, low cost, ease of use, and valuable performance, can target the low-income segment of the population. For this reason, part of the frugal innovation literature has connected frugal innovation with the concept of Bottom-of-Pyramid (BoP) (Prahalad and Hart, 1999). Bottom-of-Pyramid refers to the largest but poorest socio-economic group, the four billion people living with less than $2 per day, a group which has traditionally been ignored by the large companies, but despite their low purchasing power, constitutes a large potential market to serve. Serving BoP markets entails the idea of producing specific products for those disadvantaged consumers in the rural areas of the poor and emerging economies with the double purpose of making businesses enlarge their markets, and at the same time creating social value by improving the quality of life of less wealthy people.

In this perspective, frugal innovation stands beside the innovation approach for low-income markets; and the results section provides an in-depth analysis of the literature output in this area (Brem and Wolfram, 2014; Pansera and Owen, 2015; Agarwal *et al.*, 2017; Rosca, Arnold and Bendul, 2017).

Discussion and conclusion

Based on a bibliometric analysis supported by a qualitative approach, this study provides a scientific map of the literature of frugal innovation. The findings of the research are summarized in Table 2: research sub-fields, key theoretical lenses, key insights and future implications.

Table 2: Frugal Innovation research status

Cluster	N papers	Key insights	Authors	Areas for future research

C1: Strategic challenges	17	R&D department localization, reconfiguration of the value chain, need for different routines, human capital formations, establishment of new collaborations	Zeschky, Marco; Widenmayer, Bastian Gassmann, Olive; Ray, Sangeeta Ray, Pradeep Kanta; Winterhalter, Stephan Sharma, Arun; Iyer, Gopalkrishnan R. Neumann, Lukas; Gassmann, Oliver Shan, Juan; Khan Miqdad Ali Pandit, Deepak, Joshi, Maheshkumar P; Sahay, Arun; Gupta, Rajen K. Thun, Eric; Altmann, Peter Engberg, Robert; Altamirano, Monica van Beers, Cees P.; Lai, Wen-Hsiang Woodside, Arch; Malik, Omar R. Gupta, Budhaditya; Thomke, Stefan Amankwah-Amoah, Joseph Egbetokun, Abiodun Osabutey, Ellis L. C. von Janda S, Schuhmacher, MC Kuester, Sabine	Disentangling the relation between frugal innovation and product design; performance of frugal innovation products; how to encourage company to undertake frugal innovation strategies
C2: Inclusiveness	11	FI can have a wide variety of positive, negative, and unintended outcomes across market and nonmarket domains; its disempowering effect can contribute to create new socio-economic inequalities	Knorringa, Peter; Pesa, Iva; Leliveld, Andre van Beers, Cees; Hart, Stuart; Sharma, Sanjay Halme, Minna; Howell, Rachel; Doorn, Neelke; Meagher, Kate; Leliveld, Andre; Pesa, Iva; Baud, Isa Vossenberg, Saskia; Krishnan, Aarti Foster, Chistopher; Premi Devi, Wairokpam Kumar, Hemant; Pansera, Mario Sarkar, Soumodip	How companies can earn profits while alleviating poverty, without enhancing income inequalities
C3: Sustainable Development	7	a shift to a systemic frugal economy is the key to address the global economy challenges; models inspired by frugal	Bocken, Nancy; Short, Samuel; Prabhu, Jaideep; Jain, Sanjay; Nair, Anil	Ability of frugal innovation to fulfill multiple goals at the same time

		innovation principles could lead to positive unintentional benefits for sustainable development	Guldiken, Orhun; Fainshmidt, Stav Pezeshkan, Amir; Prabhu, Jaideep Gupta, Ravi Kumar; Belkadi, Farouk Buergy, Christian; Bitte, Frank; Da Cunha, Catherine; Buergin, Jens Lanza, Gisela; Bernard, Alain; Barlow, Allison; McDaniel, Judy A. Marfani, Farha; Lowe, Anne; Keplinger, Cassie; Beltangady, Moushumi Goklish, Novalene; Rosca, Eugenia Reedy, Jack; Bendul, Julia C..	
C4: Industrial Application	24	Fi is more efficient in terms of energy production or water purification than existing solutions and are more climate neutral; High importance of 'affordable value innovations' and 'ease of use' functionalities; Customers assign higher weightage to low or no maintenance or consumables than expected by the manufactures; FI mobile innovation have positive impacts on private sector productivity and public services provisions due to, among others, reduction of transaction length and hence costs	Levanen, Jarkko; Hossain, Mokter; Lyytinen, Tatu; Hyvarinen, Anne; Numminen, Sini; Halme, Minna Pisoni, Alessia; Michelini, Laura; Martignoni, Gloria Agarwal, Nivedita; Grottke, Michael; Mishra, Shefali; Brem, Alexander Khan, Rakhshanda Dandonoli, Patricia; Barclay, Corlane; Bendul, Julia C. Hyvarinen, Anne; Keskinen, Marko; Varis, Olli; Hossain, Mokter Rosca, Eugenia; Arnold, Marlen; Bhatti, Yasser; Taylor, Andrea; Harris, Matthew; Wadge, Hester; Escobar, Erin; Prime, Matt; Patel, Hannah; Carter, Alexander W.; Parston, Greg; Darzi, Ara W.; Udayakumar, Krishna Simula, Henri; Hossain, Mokter; Halme, Minna; Macinko, James	Comprehensive view of the effects of the application of frugal innovation to industrial system of the advanced economies

			Murphy, Jill; Goldsmith, Charles H.; Jones, Wayne; Pham Thi Oanh; Vu Cong Nguyen; Rai, Amit S. Lundin, Johan; Dumont, Guy Carbone, Sarah; Wigle, Jannah; Akseer, Nadia; Barac, Raluca; Barwick, Melanie; Zlotkin, Stanley Sun, Yuan; Cao, Haiyang; Tan, Barney; Shang, Rong-An Agarwal, Nivedita; Brem, Alexander; Grottke, Michael Kleczka, Bernadette; Musiega, Anita; Rabut, Grace; Wekesa, Phoebe; Mwaniki, Paul; Marx, Michael; Kumar, Pratap Altamirano, van Beers Aranda-Jan, Clara B.; Jagtap, Santosh; Moultrie, James Crisp, Nigel; Kuo, Anthony Harris, Matthew; Weisberger, Emily; Silver, Diana; Dadwal, Viva;	

Implications for Theory and Practice

This paper contributes to the literature of frugal innovation by providing a replicable assessment of the field of frugal innovation. Our analysis highlighted several research areas which may address new potential future research avenues. First, an additional perspective from the economists and researchers in the field of global and development studies would be useful in order to obtain a broader view of the potential impact of a more comprehensive adoption of frugal innovation. In particular, further research should attend to the potential consequences of frugal innovation to low-income economy as generating further inequalities and income gap (Knorringa *et al.*, 2016). Notably, the lack of a solid legal and institutional framework hampers attempts to promote inclusiveness and may exacerbate the income gap to the advantage of the "few" (Acemoglu and Robinson, 2010). The role of policy makers is essential to create a local network including western firms, incubators, NGOs, financial intermediates, providing the today lacking infrastructural system. In addition, most of frugal innovations are born in a local context from 'grassroot' innovators at a bricolage level, generated by the spur of the moment and lacking any structured innovation project. A proper network may also support the transferability of knowledge and the exploitation of the creative idea, as well as the creativity and the idea generation of the grassroot innovators (Altmann and Engberg, 2016). In addition, we encourage future researchers to broaden the spectrum observing the frugal innovation phenomenon through additional theoretical frameworks. To date, the most popular theoretical framework is the Bottom-of-Pyramid lens. We argue that the strong contextualization of frugal innovation with low-resource settings or BoP markets (Hart, Sharma and Halme, 2016; Knorringa *et al.*, 2016; Leliveld and Knorringa, 2018), low-income environment, India (Ray and Ray, 2011; Devi and Kumar, 2018) and Africa (Howell, van Beers and Doorn, 2018; Krishnan and Foster, 2018; Meagher, 2018; Peša, 2018), may result in a misleading consideration of frugal innovation, creating a bias in the mind of managers and practitioners in general, and reducing the sphere and the attractiveness of frugal innovation (Tiwari, Fischer and Kalogerakis, 2017).

Our analysis has identified the lack of a study of the most suitable fields of application of frugal innovation. A thorough research would help firms and practitioner to understand the most promising and suitable applications of frugal innovation, supporting their technological exploration strategy and potential cost-savings, fostering the adoption of a frugal innovation approach in firms' strategy. In addition, from a product development perspective, we encourage future researchers to address the issue of compliance to safety, standards, and compliance with legal frameworks. In addition, a stronger focus on the frugal innovation process is also recommended (Devi and Kumar, 2018).

As final remarks, we acknowledge the study's limitations, which leave room for further refinements. First, our dataset was extracted only from the ISI Web of Science SSCI. A combination with other databases would provide additional and more accurate insights about the scientific domain.

Second, by relying on bibliographic coupling as the measure of similarity, we rely on the assumption that documents that share parts of their bibliography are similar. Finally, the clusterization conducted by the software has been conducted through a content analysis on title, abstract and keywords, excluding papers not containing the keyword in their title or abstract.

The limitations of the paper offer interesting inspiring ideas to address future research efforts. Adding a temporal dimension to the analysis would provide additional insights into how the network structure of the field has evolved over time. Second, the qualitative analysis of the clusters may suffer from the subjectivity inherent in the coding procedures, which may affect the consistence of the results.

The assessment of the research field leads towards an unsolicited question: what are the next steps? The frugal innovation approach has recognized strength that make it an interesting advancement of the innovation concept: focus on core functionalities, cost reduction, complexity reduction, optimized performance, simple user centric design, and lean tools and techniques. All these attributes endow the frugal innovation with the power to fit the challenges imposed by the current major social and societal challenges: natural resource degradation, climate change, reducing poverty, and the need for sustainable solutions to slow the deterioration of the planet. In response to all these threats, a frugal approach (Tiwari, Fischer and Kalogerakis, 2017) to business and economics and to the entire way of life, appears to be one of the most effective paradigms to achieve the sustainable development goals set by the United Nations (UN, 2015). In this scenario, the role of the institutions and policy makers is crucial in terms of promoting interdisciplinary and collaborative efforts among the different stakeholders, to encourage a frugal innovation approach among companies, in conjunction with the attempts to educate people to a more “frugal” lifestyle.

APPENDIX

Visualization Algorithm

For our research, we have used a software developed exclusively for the construction and visualization of bibliometric maps and the graphical representation of such maps, VOSviewer. VOSviewer is a powerful tool to construct and visualize maps based on a large data. It can be used for instance to construct maps of authors or journals based on co-citation data or to construct maps of keywords based on co-occurrence data. To construct a map, VOSviewer uses a mapping technique developed for the VOSviewer software, called the VOS mapping technique (Van Eck and Waltman, 2007), where VOS stands for Visualization of Similarities.

The construction of the map starts from the construction of a co-occurrence matrix. After that, the software creates a similarity matrix based on the co-occurrence matrix. The similarity measure used to build the co-occurrence matrix is called *association strength* (Van Eck *et al.*, 2006), and it is calculated between objects through the content analysis of the dataset. The association strength a_{ij} of the objects (nodes) *i* and *j* is defined in general form as

$$a_{ij} = \frac{mc_{ij}}{c_{ii}c_{jj}}, \qquad (1)$$

where *m* indicates the total number of abstract, c_{ij} indicates the number of abstract where concept *i* and concept *j* occur together, and c_{ii} and c_{jj} indicates the number of abstracts in which respectively concept *i* and concept *j* occur.

Using the association strength, the similarity s_{ij} between two items *i* and *j* is calculated as

$$s_{ij} = \frac{c_{ij}}{w_i w_j} \qquad (2)$$

where c_{ij} denotes the number of co-occurrences of items i and j and where w_i and w_j denote either the total number of occurrences of items i and j or the total number of co-occurrences of these items.

After calculating the similarities, the VOS mapping technique constructs a map based on the similarity matrix obtained. Let n denote the number of objects to be mapped. The VOS mapping algorithm constructs a two-dimensional map in which the items $1\ldots,n$ are located in such a way that the distance between any pair of items i and j reflects the similarity s_{ij} as accurately as possible. Items that have a high similarity should be located close to each other, while items that have a low similarity should be located far from each other. The VOS mapping technique minimize the weighted sum of the squared Euclidean distances between all pairs of items. The higher the similarity between two items, the higher the weight of their squared distance in the summation. To avoid situations where the objects are overlapped, a constraint is imposed in the way that the average distance between two items must be equal to 1 (in this way we impose that there cannot be any overlapping objects having a distance equal to zero). In mathematical notation, the objective function to be minimized is given by

$$V\left(x_{1,\ldots.}x_n\right) = \sum_{i<j} s_{ij}\, ||x_i - x_j||^2 \qquad (3),$$

where the vector $x_i = (x_{i1}, x_{i2})$ denotes the location of item i in a two-dimensional map and where $||°||$ denotes the Euclidean norm. The minimization of the objective function is performed subject to the constraint

$$\frac{2}{n(n-1)}\sum_{i<j} \left||x_i - x_j\right|| = 1 \qquad (4).$$

At this point we have an optimization problem of minimizing (3) subject to (4).

The constrained optimization problem of minimizing (3) subject to (4) is solved numerically in two steps. The constrained optimization problem is first converted into an unconstrained optimization problem. The latter problem is then solved using a so-called majorization algorithm. The majorization algorithm used by VOSviewer is a variant of the SMACOF algorithm described in the multidimensional scaling literature (Borg and Groenen, 2005). To increase the likelihood of finding a globally optimal solution, the majorization algorithm can be run multiple times, each time using a different randomly generated initial solution. In this way, the software generates different global optima solutions with the same dataset and procedure, so the replicability of the analysis would not be guaranteed, and the results would not be consistent.

To overcome the issue, the VOSviewer software applies three transformations to the global solution:

1. Translation: the solution is centered at the origin
2. Rotation: the solution is rotated in a way that the variance on the horizontal axes is maximized (Principal Component Analysis)
3. Reflection: If the median of $x_{11},\ldots,x_{n1}$ is larger than 0, the solution is reflected in the vertical axis. If the median of $x_{12},\ldots,x_{n2}$ is larger than 0, the solution is reflected in the horizontal axis.

The three transformations ensure the replicability and the consistency of the resulting analysis.

An additional action to further increase the goodness of the results was using the fractional counting method as a normalization procedures to assign the same weight to a co-authored paper (Leydesdorff and Bornmann, 2011): fractional counting means that a co-authored publication is assigned fractionally to each of the co-authors, with the overall weight of the publication equal to one (in the full counting method a co-authored publication is counted with a full weight of one for each co-author, which implies that the overall weight of a publication is equal to the number of authors of the publication). For example, in the construction of a co-authorship network, suppose an author has a publication with other three authors. In the full counting method, the author will have three links with the other authors even if the publication is the same, while in the fractional counting method, each of the three different co-authorship links has a weight of 1/3 (Van Eck *et al.*, 2006; Perianes-Rodriguez, Waltman and Van Eck, 2016).

Once the software has created the bibliometric network, it allows to also perform a cluster analysis of the results. The cluster analysis allows to identify groups of researchers that are more connected that others. More in general cluster analysis is the task of grouping a set of objects in such a way that objects in the same group (a cluster) are more similar (in some sense or another) to each other than to those in other groups (clusters). For this purpose VOSviewer software has a unified approach for mapping and clustering (Waltman, van Eck and Noyons, 2010). The unified approach implies that the visual map already shows a clusterization operated by the software. For the clusterization procedures the software calculates the similarity matrix (calculated through the association strength as previously defined). For mapping purposes, for each node *i* there is a vector x_i that indicates the spatial location of *i* in a p-dimensional map. For clustering, the algorithm imposes to find for each node *i* a positive integer that indicate the cluster to which *i* belongs. The software algorithm assigns a node to a specific cluster by solving an optimization problem on the basis of the minimization (or maximizing, is equivalent (van Eck *et al.*, 2010)) of the function (5)

$$V(x_{i,} \dots, x_n) = \sum_{1<j} s_{ij}\, d_{ij}^2 - \sum_{i<j} d_{ij} \qquad (5)$$

respect to $x_{1,}\dots, x_n$. The element d_{ij} is the distance between nodes *i* and *j* and it is determined by the condition (6)

$$d_{ij} = \begin{cases} 0, & x_i = x_j \\ \frac{1}{\gamma} & x_i \neq x_j \end{cases} \qquad (6)$$

The parameter γ is the resolution parameter (γ>0), and the higher the parameter, the higher the number of clusters that will be obtained.

The first term of the function (4) can be interpreted as a combined effect of attractive and repulsive forces between nodes: the higher the distance and the similarity, the higher the attractiveness power. The algorithm minimizes the distance and maximizes the similarity. The overall effect of the two forces is given by the combined effect of similarity and distance.

VOSviewer uses colors to indicate the cluster to which a node has been assigned. The clustering technique used by VOSviewer is discussed by Waltman, Van Eck and Noyons (Waltman, van Eck and Noyons, 2010). The technique requires an algorithm for solving an optimization problem. For this purpose, VOSviewer uses the smart local moving algorithm introduced by Waltman and Van Eck (Waltman and Van Eck, 2013).To construct the co-occurrence map of keywords, the software extracts text data from title and abstract; VOSviewer also relies on Apache OpenNLP toolkit to identify noun, verbs, adjectives etc., where a filter identifies noun phrases (phrases that have a noun at the head of the phrase and ends with a noun) and eventually convert the plurals into singular. Some noun phrases are very general and useless for the analysis, and the VOSviewer software can detect the general ones by assigning a relevance score to each noun phrase: the ones that co-occur randomly with other noun phrases are given a low relevance, while the noun-phrases that occur mainly with a limited set of other noun phrases have a high relevance. The noun phrases with a low relevance score are dropped out, and the remaining noun phrases are the keyword terms that the software analyzes.

Chapter 2: The Performance of Alternative Innovation approach: an Agent-Based Model

Abstract

We coin the term "alternative innovation" approaches to define those driven by a focus on product functional characteristics which are "less attractive" for consumer.

We build a theoretical model and we demonstrate through an agent-based simulation that innovating on secondary functional characteristics leads to an overall final improvement of the product. The study shows how the existing concepts of alternative innovations, among others frugal innovations, low-end innovations, BoP innovations, need to be extended, because they encompass technological product innovation which can indeed improve the performance of the "conventional" complex products sold in western market, allowing further collateral benefits such as escaping from technological lock-in.

Keywords: innovation search, agent-based simulation, NK modelling, product performance, resource-constrained innovation

Introduction

The diffusion of 'alternative' approaches to innovation is led by functionalities of available products exceeding what costumers can afford or are willing to reward (Herbig and Kramer, 1992; Christensen and Raynor, 2003. These innovation models emerge as alternatives to capital-intensity technologies belonging to developed economies and, despite being known with variety of terms, they stand on the same key pillars: focus on core functionalities, removal of non-essential features, optimization of the performance, divergence from existing tools for different purposes (Tiwari, Fischer and Kalogerakis, 2017; Weyrauch and Herstatt, 2017). The outputs of such approaches are alternative versions of conventional products, whose function use is delivered through a different technology. The literature offers a variety of terms to refer to this phenomenon: among all, Frugal Innovation (The Economist, 2009; Radjou, 2012; Tiwari, Fischer and Kalogerakis, 2017); Low-end Innovation (Agnihotri, 2015), Bottom-of-Pyramid Innovation (Prahalad and Mashelkar, 2010), Bricolage Innovation (Baker and Nelson, 2005; Halme, Lindeman and Linna, 2012); Inclusive Innovation (George *et al.*, 2012; Heeks, Foster and Nugroho, 2014). These approaches have originated in resource-constrained environments to respond to the needs of the emergent consumer segment characterized by low resources and institutional constraints, therefore they are generalized as "resource-constrained" innovations (Ray and Ray, 2010; Sharma and Iyer, 2012; Zeschky, Winterhalter and Gassmann, 2014). Some notable outputs are: the General Electric low cost ECG machines and the ECG ultrasound scanning machine; the Tata portable water purifier; the Chotukool fridge; the 3D printed prosthetic leg, the C-DoT digital switching technology for communication, the origami microscope (Ray and Ray, 2010; Agarwal *et al.*, 2017). Respect to their traditional counterpart, they are characterized by the simplification of existing tools and techniques, the use of modern technology to tackle old problems and adaptation of existing tools for different purposes, and the use of low-tech approaches to meet the needs of underserved customers (Weyrauch and Herstatt, 2017).

Following Ray and Ray (2010), the attribute of 'alternative' is used to define the 'resource-constrained innovation' in contrast to the 'conventional' or 'dominant' innovation models from developed countries. The Oslo Manual (OECD, 2005) defines product innovation as "a good or service that is new or significantly enhanced, including significant improvements in technical specifications, components and materials, software in the product, user friendliness or other functional characteristics". A central element emerging from the definition is that innovation implies an improvement in technical specifications; in this respect, the phenomenon under analysis diverges from the Oslo Manual definition in the sense that it aims to deliver high value at low-cost with less focus on technical advancement and material (Zeschky, Winterhalter and Gassmann, 2014). The innovativeness is embedded in redesigning the product architecture to deliver the same function through a simplified product architecture and technology, crafting different versions of existing products (Weyrauch and Herstatt, 2017).

As mentioned above, the alternative innovation approaches are typically considered as linked with low-income and resource-constrained environments as an alternative to high capital-intensity technologies belonging to developed economies (Ray and Ray, 2010). However, although the literature emphasizes a strong connection with disadvantaged settings, there are no reasons to exclude the possibility to adopt these approaches in multiple innovation contexts.

Beyond their unquestionable social (Brem and Wolfram, 2014; Khan, 2016) and sustainable value (Rosca, Arnold and Bendul, 2017; Rosca, Reedy and Bendul, 2018), due to their affordability, no-frills architecture, minimum use of resources and optimized performance, the potential and scalability of these innovation approaches to become a general innovation model is still unexplored and unexploited.

Previous literature has introduced the concept of "optimized performance level" in relation to one type of alternative innovation (Weyrauch and Herstatt, 2017). In this respect, the concept of performance is not measured in absolute terms, but it is measured in relation to the specific context and consumers' requirements (Ray and Ray, 2010) (dominant innovation approaches have been previously criticized to "overshoot" the functionalities required by the market, resulting in innovation outputs that are overperforming respect to what customers can utilize or are willing to pay for (Herbig and Kramer, 1992). We advance the idea that alternative innovation approaches not only optimize the performance level for the targeted customers, but they enhance the whole product performance. In greater details, we consider a product as defined by a set of technical characteristics, each one perceived as more or less important by the various consumers' groups (Franceschini and Rossetto, 2002). While the conventional innovation approaches focus on exploring the technical characteristics which are preferred by most consumers (i.e. lightness or design or novelty of technology), alternative innovation approaches focus on inferior technical characteristics which are preferred by a consumers' niche (i.e. ease of use, durability, portability).

We propose a model which investigate the innovation process as technological exploration of firms which choose to deal with alternative innovation approaches, exploring the circumstances under which those models improve all the technical characteristics and thus the product performance. This design is inconsistent with the "conventional" firm's exploration behavior which features firms as competing with rivals by searching for higher quality (Banker, Khosla and Sinha, 1998; Kranton, 2003), rather than displacing competition based on cheaper output.

To test our theoretical model, we relied on a computer agent-based simulation, which accounts for the complexity of the innovation process as well as the technological exploration (Almirall and Casadesus-Masanell, 2010; Marengo *et al.*, 2012; Ganco, 2017), and provides a powerful method for advancing theory and research whereby the theory development is unable to analyze multiple independent processes occurring at the same time (Harrison *et al.*, 2007). In addition, it comes as a powerful tool to overcome the lack of empirical data, and to capture the complexity of the phenomenon (Simon, 1991).

The results show that innovating in secondary technical characteristics has positive effect on the primary ones, which is a counterintuitive respect to the view of demand condition as driver for innovation (Adner and Snow, 2010). The explanation is that alternative innovation approaches recombine old technologies in a novel design, enabling companies to harness the knowledge of old technologies to explore new and more complex interactions. Our results lead to a twofold contribution: first, we provide a theoretical framework for alternative innovation approaches which includes various resource-constrained concepts; second, we demonstrate that search over a technological space on dimensions which are not ‘popular’ among mainstream consumers allows to achieve performance improvement as through innovating on “fancy” popular technical characteristics.

Alternative Innovation search model

Innovation under constraints

The idea of innovation under constraints and the power of “doing more with less” emerges in the ’70 with the diffusion of the “Appropriate Technology” movement (Bal *et al.*, 2011), which can be described as “the simplest level of technology that can achieve the intended purpose taking adequate consideration of social and environmental ramifications. In a second moment, a broader perspective of innovation under scarce resources condition has emerged, the so-called Entrepreneurial Bricolage (Baker and Nelson, 2005), that emphasizes the organizational side of the problem and the resource-constraints become a barrier to achieve organization’s goals rather than a means to pursue social goals. A subsequent relevant step toward the outbreak of the innovation under constraints occurred at the end of the first decade of ‘2000 with the diffusion of ideas related to innovation under scarcity conditions, that literature collected under the broader category of constraint-based innovations (Agarwal *et al.*, 2017): those innovation approaches seeks to create attractive value proposition for the targeted customer groups by focusing on core functionalities and thus minimizing the use of material and financial resources in the complete value chain, and substantially reducing the cost of usage while fulfilling or even exceeding prescribe quality standard (Tiwari, Fischer and Kalogerakis, 2017).

The firms

Firms concentrate their technological search efforts in technological dimensions that are popular among consumers (Valente, 2012). Firms explore technological dimensions that support variables indicating technological function, and they need to select which of the technological characteristics (i.e., weight, materials) they want to focus on.

Following Saviotti and Metcalfe (1984), we define the technological dimensions X_i as a subset of the features describing a product. For example, a car can be considered as a complex system made of a subset of sub-systems: in our case the engine, the transmission, the braking system etc., each one defined by a certain number of characteristics (for example the engine is defined by type, size, cylinders, injection etc.). We assume that each product component is dedicated to a technical function; hence each technical characteristic corresponds to a specific component (Raja, Johannesson and Isaksson, 2018).

The demand

The demand is a crucial driver of firm's innovation activities (Utterback and Abernathy, 1975; Adner and Levinthal, 2001; Adner and Snow, 2010; Boysen, 2017). In particular, the emergence of submarkets (Klepper and Thompson, 2006), which is a subset of consumers characterized by a different set of preferences requiring a different supply-side approach, encourage firms in pursuing new innovation efforts to satisfy them.

Submarkets arise in response of the emergence of a subset of consumers with different preference schemes. These market niches stem from contexts subjected to financial, environmental and institutional constraints, typically the low-income environments (Ray and Ray, 2010; Sharma and Iyer, 2012; Agarwal *et al.*, 2017). In addition, other drivers that may lead the emergence of submarkets are: the growing propensity toward different and more "simple" lifestyle, which rewards and seeks for different values and importance assigned to product characteristics than mainstream consumers (Thompson, Hamilton and Rust, 2005; Hanna, 2012); the phenomenon of innovation overload (Herbig and Kramer, 1992), defined as the consumer's response to the increasing pace of technology and innovation due to their "over-engineering syndrome" which make them unwilling to pay for features they perceive not valuable.

Building from Valente (2012), the consumer side is modeled as equipped with a certain set of minimum requirements (one for each characteristics) that a product must satisfy to be considered valuable. The demand side is modelled as being heterogeneous, meaning that there are different consumers with different preferences and different characteristics that they prioritize. Therefore, from the demand perspective, the consumer has a set of ordered characteristics, or better *preferences*, with different priority, meaning that the m-th characteristic over the given set, is perceived as less valuable than the first characteristic. In a formal manner, preferences are defined as the ordered set of integers referring to the *m* characteristics representing the product space, where c_i represents the characteristics ranked at:
<c_1, c_2,…,c_m>, $c_i \in \{1, 2, \ldots, m\}$

Consumer are sensitive to different combination of characteristics, which are those who influence the choice of the product, and the order of the ranked characteristics represents the priority that consumers seek to satisfy: the consumer will choose the product whose characteristics will satisfy their ordered set of preferences over determined characteristics. These characteristics are represented by the technological dimensions. For instance, let us consider two distinct consumers, consumer A and consumer B: the consumer A has the ordered set of preferences defined as

A = <material, design, lightness, novelty, technological sophistication, durability, price>,

while consumer B has the ordered set of characteristics defined as

B = <portability, price, lightness, usability, durability, material>.

The two consumers have different preferences, which can be considered as expression of different technological dimensions, and for this reason they are likely to prefer different technological sophistication. In order to avoid a potential overlapping of our model with any other model with heterogeneous consumer, we must point out that in our model the consumer preferences difference deems a deeper discrepancy between those consumers that can be defined as 'conventional' and the submarket of consumers that can be defined 'alternative'. The consumers belonging to the submarkets object of our interest consider being of the utmost importance some characteristics that are normally taken for granted by conventional consumers (Creusen and Schoormans, 2005; Manzini and Mariotti, 2009; Gerasímou, 2010; Valente, 2012), thus highlighting a significant difference between the two subgroups, encouraging the firms' engagement to serve those submarkets.

Since the market demand is a driver of firm's innovation (Priem, Li and Carr, 2012), firms need to adapt their offer in order to serve the emerging submarket. As mentioned above, the requirements that those consumers expect are: focus on core functionalities, reduction of complexity and cost for final users (Weyrauch and Herstatt, 2017). In other terms, they wish for product versions that maintain the same function of their conventional counterpart, but whose purpose is delivered through a different, simplified mechanism. Firms that want to serve those submarkets need to approach innovation in a different, non-conventional way. The results of these innovation efforts are strong cost reduction, complexity reduction and the same performance level compared to their conventional opponent.

The performance level and components interaction

The functionality and cost reduction promoted by innovation under constraints may however affect the product performance. In fact, if we consider product performance as function of its technical characteristics (Franceschini and Rossetto, 2002), a decline of one or more technical characteristics after the product complexity reduction may affect the other technical characteristics and the product performance.

This effect is caused by the interaction among product components and the product architecture design (Clark, 1985; Ulrich and Tung, 1991; Chesbrough and Prencipe, 2008). Under this perspective, product performance results from the interaction among components: the more the technical characteristics and thus the components interact, the higher the complexity of the product, and a small alteration of a component impacts the other components. In this respect, each technical characteristic is associated to a specific component (Veryzer, 1998).

According to previous researches, the cumulative knowledge about a specific product architecture and components interactions occurring within a technology community is available to explore new potential applications (Cowan and Jonard, 2003; Mazzucato and Dosi, 2006; Dosi, Faillo and Marengo, 2008; Roper and Hewitt-Dundas, 2015). Given that alternative innovation relies on old, downgraded technologies, the knowledge stored over time about the components and interaction can be exploited to find new applications. To provide an example, we consider the GE portable ultrasound scanner, a diagnostic machine developed by General Electric to target a specific segment, or submarket, of consumers with specific needs and requirements. The machine was designed for the rural areas of developing countries and required specific attributes (Ramdorai and Herstatt, 2015): low complexity architecture achieved reducing the number of components (which in turn minimize the risk of breakage); ease of use, (in many cases the technicians and doctors operating in those rural areas do not have a proper training or technical skills); endurance and durability, to face eventual harsh environmental conditions such as high level of dust and humidity and fluctuations of voltage; cost-reduction, which is a consequences of the simplification of the design and the use of downgrade technologies (a conventional ultrasound machine is typically sold for more than 100.000$, compared to the portable GE alternative machine which cost 15.000$) (Immelt, Govindarajan and Trimble, 2009); effectiveness, which means that the clinical efficacy and performance is not compromised (the product has not been excluded from the rigorous certification process). This portable diagnostic tool differs from high sophisticated machines as it relies on a simple PC- and an outdated ultrasound technology, which enable the device to be plugged in any PC. The adaptability of the components makes it flexible and extremely easy to use, thanks to the underlying technologies which have been extensively explored by the technology innovation community. Furthermore, deep knowledge and control over the old technologies make easier for firms to maintain a good performance level.

Research Design

The study has been conducted through an agent-based simulation approach, which allows to reproduce a complex system associated to a mathematical model (Harrison *et al.*, 2007). Innovation and technological search have been considered by literature as complex adaptive systems (McCarthy, 2008) which are systems where the whole results cannot be understood by the decomposition of the system in smaller components, but as resulting from a complex interaction of single parts (Holland, 2006). For the purpose of the research, agent-based modelling is suitable to explore complex interaction dynamics and phenomena characterized by emergent properties.

Overview of the NK model

We choose a modeling approach in line with the purpose of our research setting: the NK-model of adaptive (fitness) landscapes (Kauffman, 1993), originally developed by Stuart Kauffmann to study the biological evolution of genome and afterward exported in management to study the searching process of new technological configuration (Frenken, 2001), the evolution and adaptation of organization forms in changing environment (Levinthal, 1997), to discover new combinations of product features (Almirall and Casadesus-Masanell, 2010), and other applications (Rivkin, 2000; Ethiraj, Levinthal and Roy, 2008; Andries and Debackere, 2013; Valente, 2014)

The NK model is defined by the landscape, the fitness function, the exploring strategy and the 'N' and the 'K'. A landscape can be defined as the space of all the possible strategic solutions defined by a fitness function (McCarthy, 2008). The fitness value is defined by a specific function that can be calculated for each point of the landscape and can be considered the measure of the "goodness" of each solution. From a managerial standpoint, there is no formal definition of "fitness", although scholars agree on its relation with competitiveness, performance, effectiveness, profitability, and as the survivability based on adaptability and durability in respect of a changing environment (McCarthy, 2004). The exploring behavior (or strategy) over the fitness landscape is also called adaptive walk over a fitness landscapes towards a "peak": the exploration algorithm is constrained around the neighboring points and is myopic because it prevents to learn from past information and predict future events, focusing on the immediate goal of improving the fitness (Valente and Aquila, 1980) (the mutation is accepted if the algorithm finds a point in the landscape where the fitness is higher than the initial condition). A possible consequence of the strategy is that the algorithm reaches a point in the landscape where the mutation algorithm gets stuck in a so-called "lock-in", because all its neighboring point have lower fitness value, and once the algorithm has found a peak, it cannot longer escape it because the algorithm does not allow that. These lock-in points are called local optima because there might be higher peak over the landscapes, that however those point the model should temporarily accept a reduction of the fitness level, to "descend" the hill of local optima, and climb the hill of the global optima. Following this metaphor, search over complex technological systems is defined "hill-climbing". Last element of the NK model is constituted by the 'N' and 'K': notably, 'N' stands for the number of components of the system, and K represent the number of interacting components within the system. The contribution of each single component to the overall performance of the system depends both on its own state and the state of the K neighboring interacting components. Furthermore, the parameter K can be considered also a measure of system's complexity, and can assumes value between 0 and N-K.

To escape the computational and technical barriers underlying the NK modelling, we draw on an extension of the NK model, the pNK-modelling approach (Valente, 2014). The pNK model is an enhanced version of NK model which circumvents the criticisms of the NK, accounting for the same features of the NK but improves its characteristics: a) real-valued N dimensional space instead of the binary, which accounted only for two possible states of the system, enabling a more realistic representation of the technological space; b) enables to consider also the intensity of the interactions through an additional parameter, and not only the number of interactions (i.e. the parameter 'K'); c) the use of a deterministic functions (rather than random values) to compute the fitness, which is simpler to implement and does not require of high computational power.

The fitness value of a point of the landscape domain is, as in NK, the average of N fitness contributions for each of the variables, and can be calculated with the formula:

(1)

$$f(\vec{x}) = \frac{\sum_{i=1}^{N} \emptyset_i(\vec{x})}{N}$$

, where $\emptyset_i$ (…) is the fitness contribution function for dimension i. While in NK $\emptyset_i$ is a random value, in pNK this is a deterministic function defined as:

(2)

$$\emptyset_i(\vec{x}) = \frac{f^{max}}{(1 + |x_1 - \mu_i(\vec{x})|)}$$

, where f^{max} is a user determined parameter indicating the maximum of the function (typically 1). Equation (2) essentially states that $\emptyset_i$ is a decreasing function of the distance between the variable's value and another function $\mu_i(x)$, defined as

(3)

$$\mu_i(\vec{x}) = c_i + \sum_{j=1}^{N} a_{ij}\, x_j$$

The NK model has emerged as a canonical approach to study how complexity affects innovation and other performance outcomes (Ganco, 2017), but the pNK model represent a way more valid, powerful and flexible tool to explore a complex system.

The pNK model for Alternative Innovation search

We investigate what happen in terms of product performance when firms pursue alternative innovation strategies. We model the innovation strategy of those firms as they focus on not-conventional technological dimensions, which are characteristics that are elementary for large-scale consumers, but are considered valuable for other subgroups. In terms of NK language, these are characteristics that display low fitness value over the technological landscapes compared to other characteristics defined by higher fitness, and therefore ignored by most firms. The fitness value measures the “attractiveness” of the technological dimension, in our model according to consumers perception. For example, technological dimensions characterized by high fitness may be the Automatic Emergency Breaking, the 360-Degree Camera or the Rear Cross-Traffic Alert, as they represent technological dimensions deemed valuable by most of consumer (Mueller and de Haan, 2009); on the other hands, technological dimensions characterized by lower fitness level may be electric glasses and central locking system, which are features taken for granted by consumers (Ray and Ray, 2011). Each landscape corresponds to a single technological characteristic. Firms choose the technological dimension to innovate considering their finite amount of resources to employ (therefore the choice of specific innovation strategy affects the other). In addition, firms explore technological dimensions innovating on the specific component associated to the specific technological dimension they are focusing, and that firms are heterogeneous and pursue different technological searches and different innovation strategies as well as serve different submarkets of consumers. In our model the supply side -i.e. the firms - is assumed to be exogeneous, meaning that we have no control over the firms' behavior.

The outcomes of the innovation strategy concern the components related to the technological dimension. As such, the overall 'goodness' of the product, i.e. the fitness, is computed as the average of the technological dimensions that define the product.

The submarkets consumers are characterized by a different set of preferences and value the technical characteristics with lower fitness that are ignored by firms. the emergence of those submarkets makes firms to adapt their strategy to serve the new submarket. In our model, the selection of the technical dimension that firms want to innovate depends on the consumer's preference schemes. However, although the selection mechanism occurs through consumer's preferences, in our model the fitness function is considered as exogenous, thus not pertaining to our control but a result of the external forces.

The innovation process is formalized as a search over a complex technological space. The outcomes of the technological search are products, made of many different interactive components, each component associated to a specific technological dimension. The way components interact may result in different possible technological outcomes.

Searching algorithm steps

In terms of firms' technological exploration, the behavior algorithm for the firm searching over the technological space follows a two-step approach:

1. Select a point and check if there are any fitness landscapes on that point which are below a certain minimum threshold.
2. If there are any fitness landscapes below a threshold minimum level, the agent concentrates the innovation effort to improve the fitness on that landscape.

3. In case more than one landscapes have the fitness below the minimum threshold the mutation is accepted or refused depending on landscape with the largest fitness gap (difference between current fitness and minimum fitness).
4. If the fitness for all landscapes are above their minimum level the decision on mutations depends on the weighted average of the fitness produced by the mutation over all landscapes.

Model Parameters

A list of the parameters defining the model is provided below. The parameters define the properties of the model and allows to run different experiment by exploring different parameter values. we run different experiment with different level of the parameter *Group (K)*.

- Parameter Group = Sets the number of interdependencies among variables, ranging from K=1, each variable depends only on itself, to K=N-1, each variable depends on all other variables (parameter).
- aij = intensity of the interdependencies (parameter). The value can range from 0 (null intensity) to 1 (maximum). The intensity affects only the variables connected, determined by parameter Group. Initialized as =1
- minx = minimum value of the initial random choice for the variables (parameter).
- Maxx = maximum value of the initial random choice for the variables (parameter).
- NBlock = Number of dimensions in "blocks". The choice of the variable(s) to mutate is done in two stages. First, the agent picks randomly a block. Then it picks randomly one variable and switch its value. Then it chooses randomly whether to pick another variable in the same block. At the end, it may choose to switch even all variables in the block. When Nblock=N there will be N blocks containing each one variable. If Nblock=1 there will be one block containing all the variables. In general, there are N/Nblock variables in each block. Choose Nblock as a divisor of N to avoid blocks of different size (parameter).

- numAgents = Number of agents in the class, i.e. using the same parameters. The main result consists in the average values over all agents in a class (parameter).
- minFitness = Minimum fitness. If the current fitness of the agent is below this value, the agent will accept a mutation just under the condition that the mutation increases the fitness on this landscape. In case more than one landscapes have the fitness below the minimum threshold the mutation is accepted or refused depending on landscape with the largest fitness gap (parameter).
- wFitness = Weight of the fitness in the decision on whether to accept a mutation or not. Agents decide primarily based on the effect on the landscape with the largest fitness gap, i.e. the difference between current fitness and minimum fitness. If all landscapes are above their minimum level the decision on mutations depends on the weighted average of the fitness produced by the mutation over all landscapes (parameter).

Simulation experiment: set-up and analysis

Experimental set-up

The analysis shows different level of interaction among technological dimensions (measured by the parameter Group (which represent the K)). The N parameter (NBlock) has been initialized as N=12, therefore the parameter Group (K) can assumes values between 1 and 11 (the maximum value for K is N-1), where 1 indicates the minimum level of interdependencies (each variable depending only on itself), and 11 indicates the maximum interaction where each variable depends on all other variables (remind that the maximum value that K can assume is N-1). The number of agents in the class, i.e. firms, has been set as equal to 10. The parameter *aij* represents the intensity of the interactions among components of the system (technological dimensions), and in our experimental set-up is kept constant and equal to 1 for all the experiment.

We run different experiments with different level of the K parameter (the number of interacting technological dimensions) with agents exploring three possible technological landscapes defined by different fitness values. We explore the results in term of performance (fitness) of the alternative innovation strategy over time. Each line represents the fitness level defined on a technological landscape. Each landscape represents a technical dimension which may be explored by an agent (e.g. firms); for that reason, we can imagine the set of dimensions explored by agents as overlapping fitness landscapes. We assume that each agent can explore one landscape (technical dimension) at the time. At the beginning, firms focus on technological dimension with the highest fitness (=1) (black line), for example the Automatic Emergency Breaking. After the emergence of the submarkets, firms move their efforts on technological landscapes with lower fitness (=0.1) (red and green), for example electric glasses or air-bag system.

Results

As we can see from the Tables 1-5, which summarize the experiment results with various level of complexity (K), the fitness value of the explored technological landscapes increases over time with various magnitude of change and degree of stability of the variation. These results show that innovating on secondary technical characteristics (maybe old and downgraded) has a positive effect on the primary technological dimensions. These results can be interpreted in terms of product architecture: the exploration of secondary, old and downgraded technological dimension may lead to explore previous technology in novel application. The established knowledge of the old technologies enables firm to uncover new components combination and to redesign the way components and technologies interact.

Simulation steps (timeline) are represented in the X-axis, while in the Y-axis we can observe the value of the fitness for each technological landscape.

We run different simulation for different values of parameter K: in detail, interaction has been explored with K=1, K=3, K=6, K=9, K=11, where K=1 represents the minimum interaction level between components (components do not interact), while K=11 represents the most complex achievable scenario with maximum interaction level of components.

The results of simulation with K=1 (Figure 1) show an overall improvement over time of the secondary technological dimension represented by the red line, while the other technological dimensions explored in turn shows constant and cyclical peaks (green line) and a decrease (black line). In terms of automotive, when the technological dimensions are not interacting (K=1), the exploration of secondary technical dimensions (i.e. central locking system and power steering) lead to a stable increase over time of only one dimension, while w observe a decrease in terms of fitness of the primary technological dimension (the black line). Unexpectedly, the technological dimension identified by the green line, although being as well a “low” fitness, does not show a stable improvement as its fitness increases only when the agents explore it, then returning to its initial condition. The results are justified by the null level of interaction between components: under this condition the focus on a single technological dimension, no the fitness level, does not affect other dimensions.

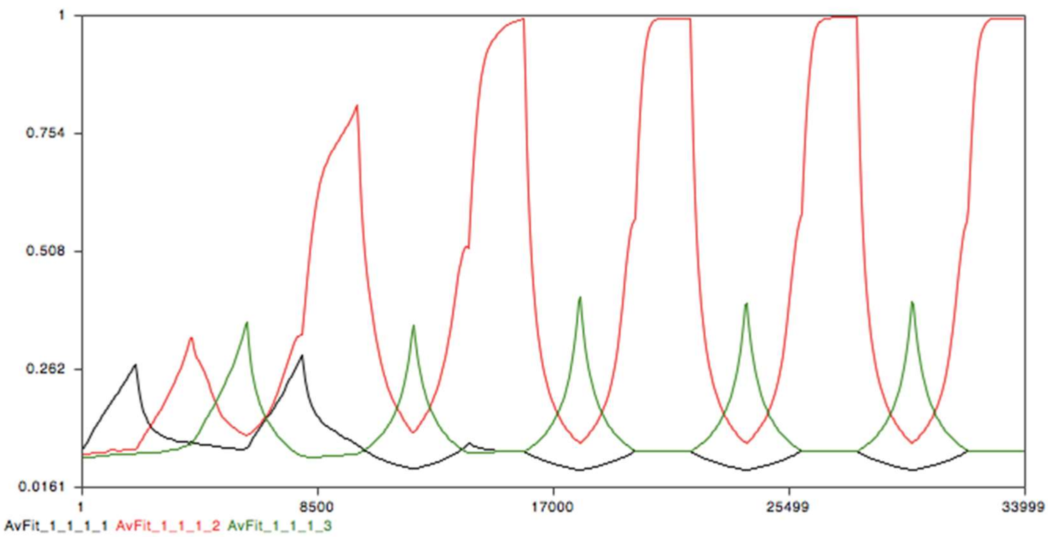

Figure 1: Group = 1, aij = 1

Table 1: average fitness for each technological dimension each time step (results for Group=1)

Group 1	**Black**	**Red**	**Green**
Time step 5000	0.541	0.109	0.098
Time step 10000	0.101	0.927	0.088
Time step 20000	0.901	0.092	0.048
Time step 30000	0.047	0.091	0.946
Time step 40000	0.090	0.998	0.090

Similarly, the results of simulation with K=3 (Figure 2), shows that when three components interact the final output improvement is not significant, but higher than the simulation in Figure 1, thanks to the higher number of interacting technical dimensions. Each technical dimension reaches a significant improvement (peak) when the agent is exploring that dimension, and subsequently return to a level close to the initial as soon as the agent change the dimension to explore. The Table 2 provides more detailed results about the performance improvement of the technical dimension: we observe a cyclical improvement for the primary technical function (black line), and a more stable, although low, improvement of the secondary technical dimensions (the average fitness for Red and Green is always greater than the beginning at Time step 5000).

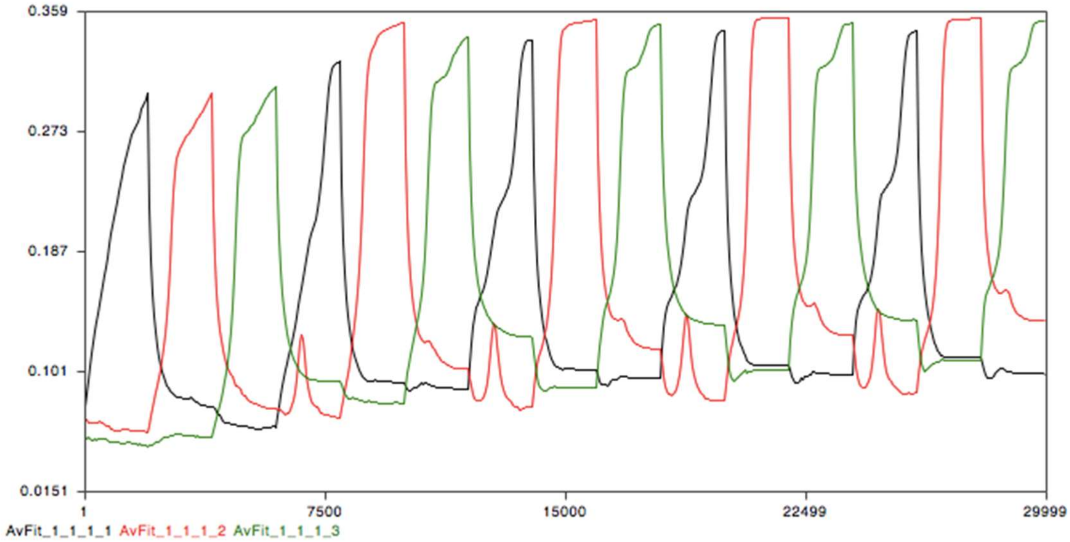

Figure 2: Group = 3, aij = 1

Table 2: average fitness for each technological dimension each time step (results for Group=3)

Group 3	Black	Red	Green
Time step 5000	0.348	0.058	0.050
Time step 10000	0.079	0.351	0.053
Time step 20000	0.335	0.075	0.092
Time step 30000	0.079	0.097	0.354
Time step 40000	0.112	0.354	0.083

The results of simulation with K=6 shown in Figure 3 show that with an intermediate level of interaction between components, we obtain a more significant and stable over time fitness improvement.

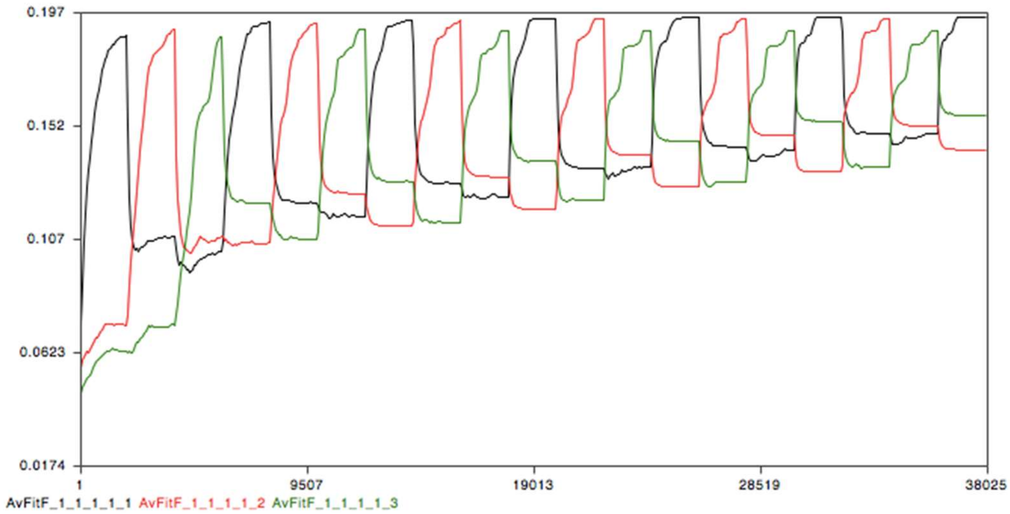

Figure 3: Group = 6, aij = 1

Table 3: average fitness for each technological dimension each time step (results for Group=6)

Group 6	**Black**	**Red**	**Green**
Time step 5000	0.190	0.067	0.063
Time step 10000	0.099	0.192	0.069
Time step 20000	0.193	0.101	0.119
Time step 30000	0.114	0.123	0.189
Time step 40000	0.128	0.197	0.110

The results of simulation with K=9 in Figure 4 shows similar results of Figure 2, with significant but not stable over time fitness improvement. Although the high number of interacting components (K=9), the results lead to incongruous results, contradicting the idea that higher levels of interaction and thus, complexity, lead to a bigger performance improvement thanks to the benefit given by the consistent interaction.

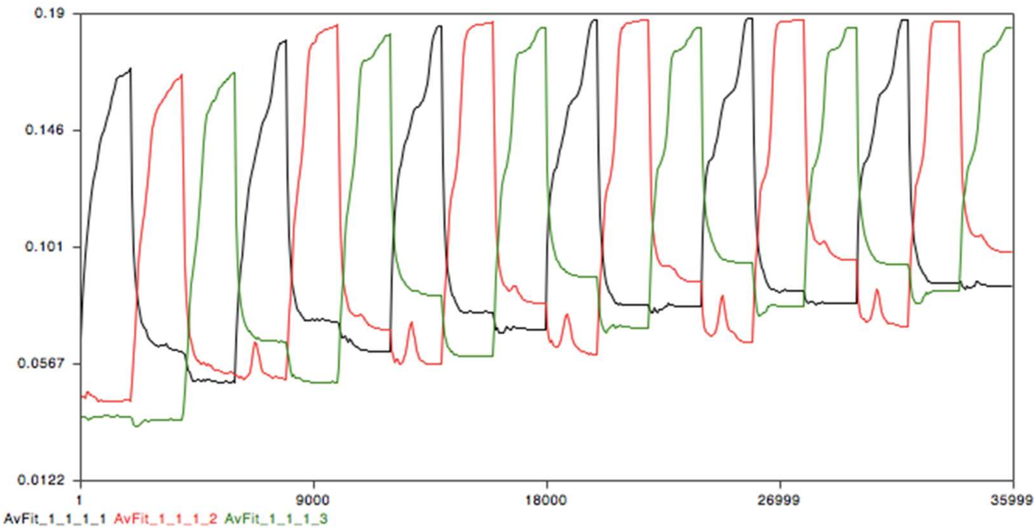

Figure 4: Group = 9, aij = 1

Table 4: average fitness for each technological dimension each time step (results for Group=9)

Group 9	Black	Red	Green
Time step 5000	0.188	0.048	0.038
Time step 10000	0.064	0.191	0.041
Time step 20000	0.187	0.057	0.073
Time step 30000	0.064	0.080	0.189
Time step 40000	0.081	0.191	0.071

The results of simulation with K=11 in Figure 5 (maximum level of interaction), show that the performance of all the technical dimension explored by agents, both with high fitness and low fitness, increases over time. The high level of interaction justifies the results: in fact, high interaction implies that even an improvement of technical dimensions that are typically ignored by agents lead to a final overall improvement of the performance of the final output, and that the improvement is stable.

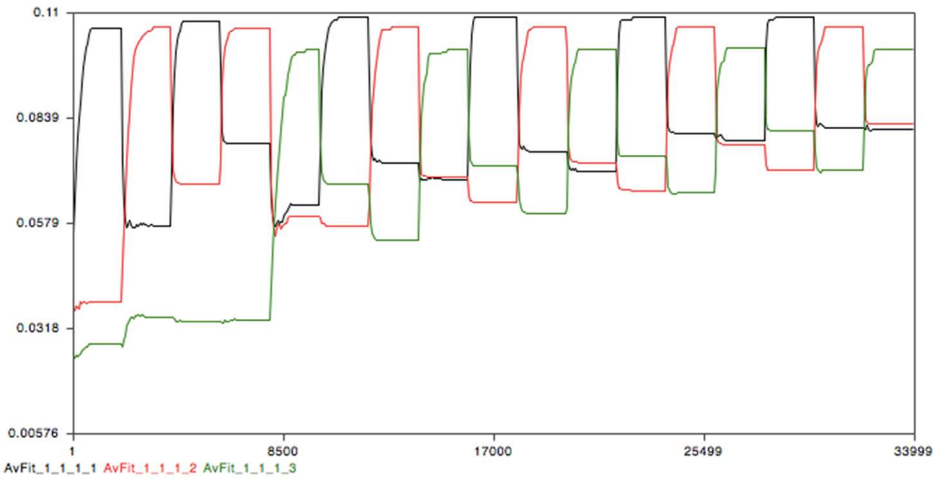

Figure 5: Group = 11, aij = 1

Table 5: average fitness for each technological dimension each time step (results for Group=11)

Group 11	Black	Red	Green
Time step 5000	0.104	0.042	0.035
Time step 10000	0.058	0.106	0.038
Time step 20000	0.106	0.056	0.067
Time step 30000	0.066	0.070	0.103
Time step 40000	0.070	0.108	0.064

The results of the simulation with K=6 in Figure 3 and K=9 in Figure 4 show conflicting results: with K=6, the overall increase of the lowest fitness level is ultimately higher than the simulation with K=9, which indeed shows similar results to simulation with K=3. In fact, we expect that an increase of interaction intensity results in greater improvement of the performance (as the minimum level assumed by the fitness function over time increases), as higher level of interdependences has a positive effect on the overall performance.

An explanation for the results can be found in the combined effect of the high complexity and the non-interacting technological dimensions. First, the high complexity given by nine interacting technological dimensions (on a total of twelve) meaning that any change in a dimension affects the others, hindering the improvements of all the technological dimensions and the related components. Second, the non-interacting components (three in this case) act as a bottleneck or reverse salient (Hughes, 2012), meaning that a component of technological system that, due to its insufficient development, prevents the entire system from achieving its maximum performance goals. Although they do not interact neither with other components nor each other and as consequence they do not benefit from any improvement on the interacting components, they prevent other technological dimensions to maintain the progressive performance improvement achieved step-by-step. On the other hand, with full interaction level (K=11) all the technical dimensions and their related components interacts, and despite the high complexity, the absence of non-interacting components allows to take full advantage of the interaction.

Discussion

We model the technological exploration of firms pursuing an alternative innovation strategy and we demonstrate through an agent-based simulation that when the number of technological dimension interacting is high or intermediate, the exploration leads to a stable improvement of the product performance (Table 6), while low and intermediate-high number of technological dimensions interacting, the performance improvement is not stable.

Table 6: Summary of results

Interaction Parameter	Results
K=1	null performance improvement
K=3	small and stable performance improvement
K=6	significant and stable performance improvement
K=9	medium and stable performance improvement
K=11	significant and stable performance improvement

The results of the theoretical model can be read under different prospects. First, it is reasonable to reflect on the need of technological advancement. If it is possible to obtain good performance with less, what is the driver of technological innovation seeking for bigger and bigger advancement? Second, alternative innovation approaches enable to give a new life to old, downgraded technologies. Following Raffaelli (2019), which allows the reemergence of legacy technologies as consequences of market redefinition, our results account for the possibility for the reemergence of an old technology to meet new purposes and to solve different problems. Building on the previous point, alternative innovation strategy may be analyzed in terms of their effect on the development of technological trajectories (Dosi, 1982), which are defined as cluster of possible technological directions whose boundaries are defined by a set of rules (technological paradigm) defining the rules to solve problems. Those trajectories determine the path and the direction of advancement on which technological progress occurs (Nelson and Winter, 1977), and once established, they are very difficult to abandon. In this respect alternative innovation strategies may be a new set of rules to solve problems: once the established technological paradigm is not able to tackle emerging problems, adaptation of old technologies for different purposes and different innovation approach may constitute a split-off which could prevent an expensive establishment of a new technological trajectory. Fourth, the split-off may constitute a way to escape from lock-in (Cowan and Hultén, 1996). The lock-ins are technological regimes that once are established, are extremely difficult and costly to abandon (Cowan, 1990). Consequently, they tend to persist for extended periods, even in the face of competition from potentially superior substitutes and are characterized by significant difficulty to abandon them. In this perspective, alternative innovation approaches, by targeting niche submarkets through the reconfiguration of downgraded technologies, enable to escape from the previous trajectory and to explore additional technological configuration. In fact, exploring alternative and less-valued technical dimension with lower fitness value implies to innovate on lower fitness technological dimension for a short time, which in turn enables to assume a different point of view of the technological landscapes, being able to capture new innovative technological configurations, which would have otherwise unexplored.

When GE Healthcare, a division of the General Electric Company, decided in 2005 to develop a low-cost electrocardiogram (ECG) device for developing economies, the senior business leader was facing a dilemma concerning the difficulty "to take out engineers from projects that are sure to give high returns" and move them into an uncertain and undefined project (Ramdorai and Herstatt, 2017). However, the project resulted in the MAC 400, an ECG costing $1000, ten times less than its high-end competitors and about 30% less than the least expensive GE ECG machine sold in the Indian market, and whose value proposition was cost advantage, portability and robustness to work in harsh environment. The head of the project also noted how they accepted that the return on investment will be on a long-term, strategic investment (Ramdorai and Herstatt, 2017). Forsaking the "comfortable zone" and broadening the perspective toward the technological landscape and undertaking questionable actions, GE has "escaped" from the previous technological trajectories and has overcome it. Any future attempts to return on the previous technological trajectory would have failed, because the GE's alternative exploration has led to a development of new technological skills and set of procedures which allowed the company to escape the technological lock-ins. In fact, after the development of the first MAC 400, GE has developed a series of following version, the 'MAC i', a device with a superior cost-optimized design than the previous MAC 400, and subsequently the MAC 600, a more sophisticated version of MAC 400, and finally a further enhanced version, the MAC 800, priced $2000 and sold in the USA. The performance of the last, optimized version of the ECG machine meets the required standard for being sold in a sophisticated, developed market like USA. The example shows how the outcome was a product which differs from the conventional design yet performing. In our terms GE has escaped the technological lock-in.

A similar example is the case of no-cash payment system developed by Alipay in China: the QR-code payment (Lerong, 2018). The payment takes place by scanning a QR code with the smartphone camera connected to a specific payment app, which process the transactions. An infrastructural constraint like a proper financial and bank structure in China, has resulted in the developing of an alternative and better performing technology, which has escaped from the technological lock-in of the POS technology, the established technology for electronic payment in developed economies, and which has the potential to further innovate following a new technological trajectory.

Conclusions

In this study we developed an agent-based model to explore the circumstances affecting the performance achieved through alternative innovation approaches. Our research provides a theoretical model which collect the various concepts of innovation under constraints through their peculiar and common characteristics, and which represents a common innovation strategy depicting the main features of all the approaches.

We contribute to the developing literature on resource-constrained innovations by providing and testing a theoretical model of the performance level of the output of those approaches. Furthermore, to a lower extent, we offer an alternative view about how to escape from technological lock-in providing a unique vision of the potential benefits of technology re-emergence.

Finally, in line with the literature of innovation overload, we confirm that there is an option to the over-innovation, and this option is innovating less although in the right technological dimension, which may not be the one with the higher value for consumers or the higher fitness (Herbig and Kramer, 1992; Christensen and Bower, 1996); a subsequent issue to better investigate, which may pose the basis for a future research, may be which is the relevant technological dimension to put the effort on.

We acknowledge that agent-based simulation has its recognized limitation. First, the choice of the parameters to vary in the experiment. Second, the interpretation of the parameter may not be straightforward and related to the real-world phenomena. Wherever possible, however, we tried to show the input validity of our parameters providing empirical examples supporting them. Third, in line with a universally recognized limitation of agent-based simulation (Burton and Obel, 1995; Rhodes, Holcombe and Qwarnstrom, 2016), the need to represent a small portion of the scenario implies a forced simplification of the reality and the risk of losing relevant detail, whose inclusion, however, would result in a too complex scenario, compromising the understanding of the obtained results (in line with the model building procedure KISS - Keep It Simple, Stupid (Colman, 1998)).

However, the analysis of the simulation results depicts a scenario that allow us to draw some preliminary implications for theory and practice. First, the results show that firms that have a deeper knowledge over a certain technology might have an advantage in exploiting that technology for a different purpose, as they own a deep knowledge of the dynamics of the technology. This advantage may be further exploited the higher the interdependencies among parts are. This fact should not discourage firms in abandoning downgrade technologies, but otherwise to further explore them with the perspective of giving them new like in the shape of new innovative applications that are “revolutionary” and atypical. Also, managers could benefit from a reduction of time and cost of product innovation thanks to the deep knowledge of the previous technologies.

Finally, we must acknowledge that without a shift towards a different consumption behavior from the consumer side, the emergence of submarkets of consumers, susceptible to "inferior" technical characteristics which spur companies in moving towards alternative innovation approaches, will be slackened. In this regard, following Chancellor and Lubomirsky (2011), who criticize materialism and over-consumption as harmful for the individual, the economy and the environment, we advance the role of marketing and psychology as a source of influence towards different consumption approaches, with the purpose of delivering the same hedonic benefit as per the conventional product, together with policy makers, which may strive to push the society towards a more efficient and effective use of resources.

Chapter 3: Modelling the Product Complexity and Frugal Innovation from a Product Architecture approach: a pseudo NK model

Abstract

This paper assumes a product architecture perspective to analyze the phenomenon of frugal innovations as counterpart of existing products. Addressing the importance of the design and product architecture for product performance, the paper explores the dynamics of interaction behind frugal innovation architecture, and the circumstances which lead frugal innovation to an increased performance. We provide a theoretical model for firms exploring the innovation space with frugal innovation strategies that we subsequently test through an agent-based simulation model. Our results show that frugal innovation leads to performance improvement if the number of interacting technological functions is low and the intensity of such interactions is very high, or whether the number of interacting technological functions is high and the intensity of interaction among them is medium. The results constitute an important avenue for future research and to foster institutions to advance adequate policies.

Keywords: frugal innovation, product architecture, product performance, agent-based simulation, NK model

Introduction

The demand for products whose performance and sophistication does not exceed the minimum functional requirements is leading firms to move toward different approaches to innovation. A potential source for these novel approaches is the one developed in low-income environments facing environmental, financial and institutional constraints and under general conditions of scarcity. These approaches have spread in business press and then in the academic debate with different names, and although with minor differences, they are built upon the same pillars: focus on core functionalities, low-price and high performance (Weyrauch and Herstatt, 2017). Among others, these approaches are known as Frugal Innovation (The Economist, 2009), Bottom-of-Pyramid Innovation (Prahalad and Hart, 1999), Grassroot Innovation (Brem and Wolfram, 2014), Jugaad Innovation (Radjou, Prabhu, 2012). However, the literature has gathered these notions under the umbrella of Resource-Constrained Innovation (Ray and Ray, 2010), which captures the most impactful traits of the approaches.

Despite the context is often limited to low-income, underdeveloped economies, the growing interest of consumers from western economies in “less-fancy” and less “technologically sophisticated” products are broadening the scope of resource-constrained innovations, spanning its boundaries towards a more global outreach (Tiwari, Kalogerakis and Herstatt, 2016). These consumers can be defined as a submarket niche (Klepper and Thompson, 2006), meaning a subset of consumers with different set of preferences than mainstream counterparts. These consumers are affected by “innovation overload” syndrome (Herbig and Kramer, 1992), meaning that they react to the ever-increasing pace of technological innovations by refusing such complex alternatives that overshoot the functionalities required by the market. Besides, the increased attention towards environmental and sustainable themes, which suits with the principles of resource-constrained innovations paradigms, is moving innovative firms towards the aforementioned approaches. For the purpose of our article, we henceforth refer to frugal innovation as representative of resource-constrained approaches, because it constitutes the common denominator of these approaches (Lim and Fujimoto, 2019) and because it is the most analyzed subtopic in the growing academic field (Bhatti *et al.*, 2018), and provides a richer understanding and insights about the regulating mechanism for the purpose of further researches.

Frugal innovation is far from a pure low-cost adaptation of products that can be found in western economies (Zeschky, Winterhalter and Gassmann, 2014), but it encompasses a new product architecture that enables new product applications and configurations at lower price than the traditional counterparts, without penalizing a good performance level. Extant research has focused on the distinguishing features (Agarwal *et al.*, 2017; Hossain, 2017; Rao, 2017; Pisoni, Michelini and Martignoni, 2018), strategic challenges for firm's adoption (Zeschky, Widenmayer and Gassmann, 2014; Winterhalter *et al.*, 2017), the implications in sustainability issues (Bocken and Short, 2016; Rosca, Reedy and Bendul, 2018) and potential applications (Hyvärinen, Keskinen and Varis, 2016; Agarwal, Brem and Grottke, 2018; Altamirano and Beers, 2018), with a weaker attention to the "hard" aspects of frugal innovation issues and the technical properties, the architectural domain and the possibility to obtain a good or even improved performance level with less resources (Ray and Ray, 2010; Altmann and Engberg, 2016; Lim and Fujimoto, 2019), and the safety and performance of frugal innovation applied in advanced science (Rao, 2017).

Our study builds on this research gap and focuses on the complexity of interactions among different technical dimensions (modelled as technical functions) of frugal innovation products and how the final performance is affected by those elements of complexity. In detail, we assume that a general product can be defined through its technical characteristics and that the intensity of interaction among those technical characteristics can be translated in terms of product complexity, we analyze which are the optimal condition of product complexity to obtain a stable and high-performance level for a frugal innovation design.

The study has been conducted through an agent-based modelling approach. We modelled the explorative innovation process of firms engaging in frugal innovation activities which focus on secondary technological dimension and aim to reconfigure them to obtain a significant performance improvement of all the technical characteristics. These results that are not straightforward, because the improvement and in general the alteration of a technical characteristic does not lead by default to the improvement of the others and the overall products. In fact, the alteration of a technical characteristic in terms of improvement may lead both to the improvement of the others but also to the worsening of another one or, in the worst-case scenario, all the others.

Our results show that firms that want to adopt a frugal innovation approach obtain a greater "design" architecture and performance improvement if the number of interacting technological dimensions is low and the intensity of such interactions is very high, or whether the number of interacting technological dimensions is high and the intensity of interactions among them is medium.

The paper contributes to the growing literature and scientific debate on frugal innovation phenomenon, providing a bridge between the literature of product architecture and design, and the frugal innovation literature. A foremost contribution of this research is given by the promotion of frugal innovation not only as a low-cost solution to meet the needs of rural and low-income economies, but also a technological product innovation paradigm that encompasses strengths and weaknesses and that cannot be circumscribed to a specific context.

Theoretical Background

Emergence of submarket as a driver for innovation in firm's innovation decision

According to the market creation approach, the market is considered the 'pulling' agent of technological innovation (Adner and Snow, 2010; Klepper and Malerba, 2010; Boysen, 2017). Users and consumers are essential part of the innovation process (Von Hippel, 1986), as well as the user-producers interaction (Lundvall, 1988) and a failure in understanding and/or anticipating the evolution of the demand needs can lead to the market failure (Christensen and Bower, 1996; Weber and Rohracher, 2012). As consequence, the demand drives the emergence of new industries and technologies (Greenstein, 2010), and such industry evolution is driven by the birth and death of submarkets within an industry (Klepper and Thompson, 2006). These submarkets are subgroups of consumers characterized by different sets of preferences; the heterogeneous demand ok submarkets leads firms to accommodate their offer to meet the requirements of the submarkets (Valente, 2012).

In this respect, a change in innovation process can be viewed as an adaptation to the emerging market needs.

Frugal innovation in relation to product and design

Frugal innovations can be defined as the simplification of existing products by reducing its functions, components, processes and interconnections (Lim and Fujimoto, 2019). Such simplification results in a specular version of existing complex products, whose functional requirements are reduced, thus not hindering the key functionalities or the optimal performance level required by the consumers (Bhatti, 2012). The key pillar identifying frugal innovation are: focus on core functionalities, significant cost reduction (resulting from design simplification), and optimized performance level for the intended purpose to meet the consumer's requirement (Weyrauch and Herstatt, 2017). The application of such approach to innovation varies along a continuum constituted by different level of complexity, varying between low complex products such as a light bulb and more complex products such as cars (Ray and Ray, 2011), medical devices (Immelt, Govindarajan and Trimble, 2009), and the telecom digital switching system (Ray and Ray, 2010).

The Tata Nano cars represents one of the most acknowledged examples of frugal innovation: launched in 2009 as the world's cheapest car by the Indian conglomerate Tata, it performs the requisite functions of a car through a simplified product design (no base power steering, trunk accessible only from inside, one windscreen wiper, thinner space saver spare tyre, no CD player or power windows) (Ray and Ray, 2011). Other notable applications belong to the healthcare area. The most diffused medical devices designed under the logic of frugal innovation are produced by GE: notably, the Mac 400 ECG machines and the GE low-cost image diagnostic machine developed for Chinese and Indian market (Immelt, Govindarajan and Trimble, 2009). The simplification of the design relies on the use of old, downgraded technologies adequately reconfigured: the Mac 400 device works on old downgraded microprocessors, and the diagnostic machine can be plugged in any PC and relies on inferior downgraded ultrasound technology. The telecommunication industry has not been immune: the Rural Automatic Exchange (RAX) is a small rural automatic exchange for telecommunications developed by the Indian telecommunication technology development center (C-DoT). It is designed specifically to meet the conditions of the rural Indian areas and provides telephone connections with a very basic infrastructure (Ray and Ray, 2010). To focus on core functions, they removed highly specified features such as "conference calls" and "call waiting". To overcome the harsh environmental conditions and the lack of technological infrastructures such as the lack of high voltage electricity, they exploit the design as a mean to overcome the barrier: as cooling system, typically characterized by high consumption, they used low-powered microprocessors and they spread the electrical circuit more than the usual, to enable the heat to dissipate easily.

Frugal innovation seen as architectural innovation with minor technologies

The frugal innovation approach can be seen as an architectural innovation (Lim and Fujimoto, 2019), because the magnitude of innovation relies mostly into the innovation in design sphere. Architectural innovations can be defined as "a change in the way in which components of a products are linked together, while leaving the core design concepts (and thus the basic knowledge underlying the components) untouched" (Henderson and Clark, 1990:10).

The product architecture is the scheme by which the function of the product is allocated to physical components and can be a key driver of the performance of the manufacturing firms (Ulrich, 1995). The product functions refer to any attributes of the products from which the user takes benefit. Any product can be divided into many subcomponents, each one implementing different functions (Clark, 1985; Ulrich, 1995). The product architecture embeds the knowledge about the higher-level framework in which the components are integrated and operate as a coherent whole system. Components may be connected through physical interfaces or non-contact interactions, which have specifications to allow the interface to "communicate" with the parts to connect (most of the interfaces adhere to standard protocol) (Mikkola and Gassmann, 2003). The matching between functional elements (what a component does) and physical components can be one-to-one, resulting in modular architecture (Langlois and Robertson, 1992), or a complex (non-one-to-one) matching between functions and physical components, resulting in integrated architecture (Ulrich and Seering, 1990).

Frugal innovation under the light of architecture and design

We imagine integral and modular architecture as defined by the intensity of interaction about components (representing the functional requirements desired by consumer). A modular architecture corresponds to a lower intensity of interaction among components, as each component is associated to one single function and performs a well-defined function, while an integral architecture corresponds to high intensity of interaction among component, having various functions performed by various physical components and vice versa (Mikkola and Gassmann, 2003).

Functional elements in product architecture represent the function performed or the benefits the elements carry (Ulrich, 1995). We can imagine functional elements as representing the functional technological dimension appreciated by consumers. Each subset of consumers, or submarket, is characterized by a specific set of technological dimensions ranked in a specific order, defining the hierarchy in terms of perceived value associated to each technological dimension and, as consequence, to each corresponding functional element (Raja, Johannesson and Isaksson, 2018).

Frugal innovation can be considered a variation of architectural innovation because it entails change in the way component interact (relying on old, downgraded technologies) thus maintaining the core design of the products untouched (focus on core functionalities). While the mechanisms of "pure" architectural innovation in the form of modular or integral product is known as well as the dynamics of the outputs and the variables affecting the resulting performance, the dynamics behind frugal innovations architecture and how the reconfiguration of components affects the performance may differ (Lim and Fujimoto, 2019). In addition, when the frugal innovation changes significantly its architecture or components, the past knowledge of the interdependencies among components may be lost, requiring a new exploration of the components interaction in the new design (Chesbrough and Kusunoki, 2012).

Performance of frugal innovation product

Product performance is how well the product implements its functional elements (Ulrich, 1995). The product performance can be measured based on its operational dimension (Alegre, Lapiedra and Chiva, 2006) or based on the consumer's perception (Olshavsky and Miller, 1972). The notion of product performance can be related to the concept of fitness as a measure of its "goodness" in relation to a particular environment (McCarthy, 2004). According to this view, the external environment shape and determine the survival of the "fittest", i.e. the products whose innovativeness and performance match the best requirement for the environment (landscape) (McCarthy and Tan, 2000). The demand side (consumers) plays a crucial role in determining the optimal fitness level. Each product innovation is evaluated by consumes based on the functionalities it ensures; as such, product performance is a result of the combined effect of value of functionalities delivered by the innovation and the consumers' value attributed to each product functionality (Veryzer, 1998).

Despite its peculiar feature such as working on constrained environments, under resource scarcity conditions and in light of reduction of non-essential components, frugal innovation has showed to improve the performance of the product deliverable to the lower end of the mass market (Lim and Fujimoto, 2019): in this respect, frugal innovation represents a technological product innovation that may improve the performance of relatively complex products deliverable through their architectural changes (Henderson and Clark, 1990). In addition, frugal innovation has demonstrated to exceed these results by meeting the exact performance level desired by extant consumer (Weyrauch and Herstatt, 2017), which is often overload by current offer and it threaten some consumers (Herbig and Kramer, 1992).

Model structure

To conduct the research, we adopted a pNK modelling approach. The pNK model (Valente, 2014) is an extension of the Kauffman's NK model (Kauffman and Weinberger, 1989), developed to study the biological evolution of genome, and then introduced in the management studies by Levinthal (Levinthal, 1997). The NK model replicates a complex system searching over a complex landscape, with N representing the number of components of the system and the K represents the number of interacting components (it can assume values between the range $0 \leq K \leq (N-1)$). The contribution of each single component to the overall performance of the system depends both on its own state and the state of the K neighboring interacting components. The search process occurs over a landscape defined by peaks and valleys. In each point of the landscape is it possible to compute the fitness, that can be defined as the measure of goodness of a solution in that point: points in the landscape corresponding to hills will have higher fitness that point in the valleys. The NK model allows to represent the architecture of a product (the set of the components N) and a set of interacting components defined by K.

The pNK model is an enhanced version of NK model which accounts for the same features of the NK but improves its characteristics: a) a real-valued N dimensional space (instead of the binary space in the regular NK, only two possible states of the system are enabled), enabling a more realistic representation of the technological space; b) an additional parameter ‘a’ measuring the intensity of interaction among system components; c) the use of a deterministic functions (rather than random values) to compute the fitness, which is simpler to implement and does not require high computational power.

The fitness value can be computed on any point in the landscape as the average of N fitness contributions for each of the variables, and can be calculated with the formula in (1):

$$f(\vec{x}) = \frac{\sum_{i=1}^{N} \emptyset_i(\vec{x})}{N} \qquad (1)$$

, where $\emptyset_i$ (…) is the fitness contribution function for dimension i. While in NK $\emptyset_i$ is a random value, in pNK this is a deterministic function defined as in (2):

$$\emptyset_i(\vec{x}) = \frac{f^{max}}{(1+|x_1 - \mu_i(\vec{x})|)} \qquad (2)$$

, where f^{max} is a user determined parameter indicating the maximum of the function (typically 1). Equation (2) essentially states that $\emptyset_i$ is a decreasing function of the distance between the variable’s value and another function $\mu_i(x)$, defined as in (3):

$$\mu_i(\vec{x}) = c_i + \sum_{j=1}^{N} a_{ij}\, x_j \qquad (3)$$

The agents: the firm

The firms are modelled as agents active in the innovation searching process over technological landscapes. We focus on product innovation activity as defined in the Oslo Manual (OECD, 2005:46): firms pursue innovation activity searching over the technological landscape (which is considered exogenous) defined by various technological functions, which in turn define the products’ technological dimension (e.g. lightness, durability, portability, technological sophistication). Firms introduce innovations by experimenting with different combinations search over the landscape (Levinthal, 1997). The agents explore the landscapes searching for points where they improve the fitness of the technological dimension they are exploring. The improvement of the fitness given by firms exploring technological landscapes, ergo innovating, can be translated into enhancement of product performance.

In a more formal definition, the technological dimension can be interpreted as a vector of ordered technological dimension, where the m-th dimension has a minor relevance for the firm:

$$X_i = (X, X_2, X_3, \dots \dots \dots \dots, X_m)$$

The demand: the submarkets of consumers

Consumers are an essential element of the model, as they drive firm's innovation activity (Adner and Snow, 2010; Boysen, 2017). Consumers make their purchase decision on the base of their preference scheme. In the consumer's panorama, we hypothesize two classes of consumers: the "mainstream" consumers, which represent most consumers showing a common preference scheme, and a class of consumers made by carious niche of consumers which have peculiar preferences schemes and differ from the mainstream ones. These subsets of consumers can be considered as submarkets (Klepper and Thompson, 2006), emerging as a class of consumers whose different set of preferences requires a different supply-side approach. As the set of preferences is ordered, the first technical dimension in the list is the most valuable and the last is the less important. The emergence of the submarkets constitutes a driver for firm's growth, thus requiring a different approach to serve them, including alternative innovation efforts. In this model, the submarket is constituted by consumers interested in secondary technological dimensions, which are typically taken for granted by the mainstream consumers.

The set of preference can be represented as a vector where the preferences are defined as the ordered set of integers referring to the m characteristics representing the product space (Valente, 2012), where c_i represents the characteristics ranked at:

$$<c_1, c_2, \dots, c_m>, c_i \in \{1, 2, \dots, m\}$$

The N and the K

We model technological dimensions as expression of functional elements associated to different component. Each component can perform a single function (modular architecture) or multiple functions (integral architecture).

Firms (agents) pursue the process of innovation as a search for novel combinations of existing components (Schumpeter, 1934; Henderson and Clark, 1990).

In this model, the N stands for the number of technological dimensions that the agents can explore as expression of the functional elements, while the K (in our model, K correspond to the parameter 'Group') stands for the number of interacting functional elements within the system. The interacting functional elements translate in interaction between components. An example of interacting functional elements are the brake system and the vehicle mass, in the automotive industry. The K defines the level of complexity of the system: with K = 0 there are no interacting elements, while K = N-1 correspond to the case where all the N elements of the system interact. Noting that the pNK

model allows to control also for the intensity of interaction among components, we model such intensity with the parameter 'aij'.

The simulation designs

The simulation settings have been initialized with a single simulation run in 50000-time step. The initialized value for the landscapes has been set equal to three (for time and computational effectiveness). The number of components in the systems has been initialized equal to 12 (N = 12), and the intensity of interaction among components (i.e. technical characteristics) in the range between 0 and 1 ($0 \leq aij \leq 1$). The number of agents is determined as a random extraction in the range between 60 and 150. Each technological dimension is associated to a specific landscape, where is consequently possible compute the fitness value at each point of the landscape. Each product resulting from the agent's innovation activity is defined by a set of technical dimensions, each having a certain fitness level. Therefore, it is possible to compute the overall fitness of the product output of the innovative search as the weighted average fitness of the technical characteristics defining that product (the weight depends of the importance of the technical dimension in the consumers ordered set) (Fig 1).

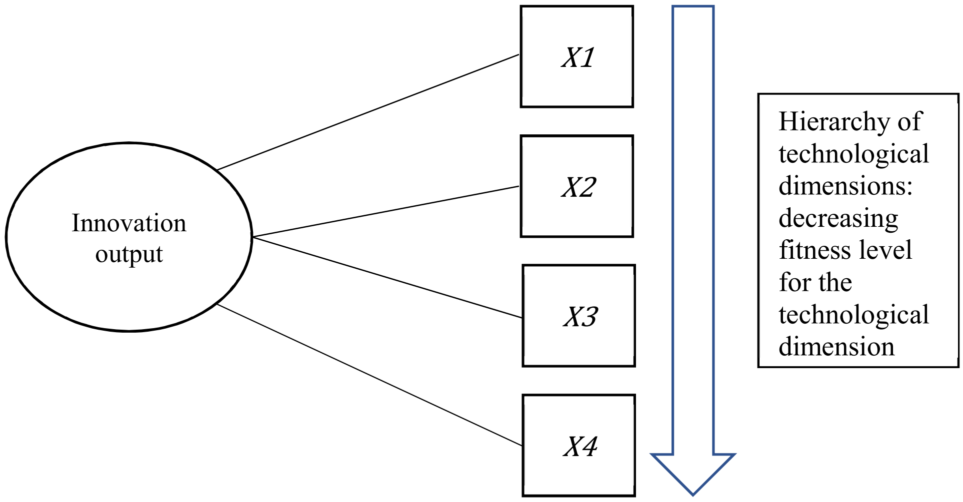

Figure 1: Representation of innovation output as defined by hierarchical functional elements

Model Results

The analysis has been conducted exploring different configurations of the parameters, replicating an experimental design. The LSD platform has been used (Valente, 2008). We run two sets of simulations, each one keeping constant the parameter Group, (representing the "K" of the pNK model), at two different level (Group = 2 and Group = 8) and varying the "aij" parameter (representing the intensity of interaction). In this way we modelled different situations of number of interacting components.

A more in-depth explanation for the choice of varying 'Group' and 'aij' is provided in the Appendix. The parameter 'aij' can vary in a range between 0 and 1 (as per pNK model design). The results provide insights of the effect of different levels of intensity of interaction (at two different level of 'Group') on the average fitness of the innovation output. The results show that innovative efforts on secondary technological characteristics results in an increase of the fitness of the "mainstream" technological dimension.

The graphs show the average fitness (Y axes) over time (X axes). The different colored lines represent different technological characteristics (explored over different landscapes). These technological characteristics are defined by a fitness respect to their landscape, and this fitness measure the "attractiveness" of the technological characteristics from both the demand and the supply side: from the supply side, it represents the technological characteristic that firms concentrate more on because the demand side (consumers) recognize as more valuable and give priority to them. The black line represents a technological dimension which is valued by most of the consumers, that can be defined as "mainstream", while the green and red lines correspond to technological characteristics which the majority of consumers perceive as standard and taken for granted while the submarket of "frugal" consumers consider of worth. The emergence over time of the new submarket[2] of consumers which regard secondary technological dimensions that are taken for granted by most of the consumers (green and red lines), causes the alternation of peaks of different technological dimensions in terms of average fitness of the technological output. This occurs because firms engaged in innovation activities start to innovate in the new technological dimension (green and red lines increase) valued by the submarkets. The simulation experiments explore different combination of parameter measuring the intensity of interaction between the different technological characteristics and how these combinations affect the output's final performance.

The first set of simulations (Figure 2 – Figure 5) shows different configurations of the parameter 'aij' keeping the parameter Group constant and equal to 2. We can observe from the simulation results in Fig. 2, that with a low number of interacting technical characteristics

[2] We consider the emergence of the submarket of consumer interested in "less-valuable" dimension or affected by innovation overload syndrome or budgetary constrained. However, we do not exclude the possibility of other submarkets to emerge, which will not be considered for the purpose of this study.

(Group = 2) (the highest value that the parameter can assume in the model is 12) and the parameter 'aij' measuring the intensity of those interaction equal to zero (aij=0), there is an initial increase of the fitness of the technological dimension identified by the black line (the technological dimension regarded by the majority of consumers, which become secondary as the submarket emerges over time), but the overall increase over time is stable. This is due to the interaction intensity parameter '*aij'* equal to zero, meaning that there is no interaction between the technological dimensions explored by innovative firms, and the focus over a single technological dimension does not affect the others.

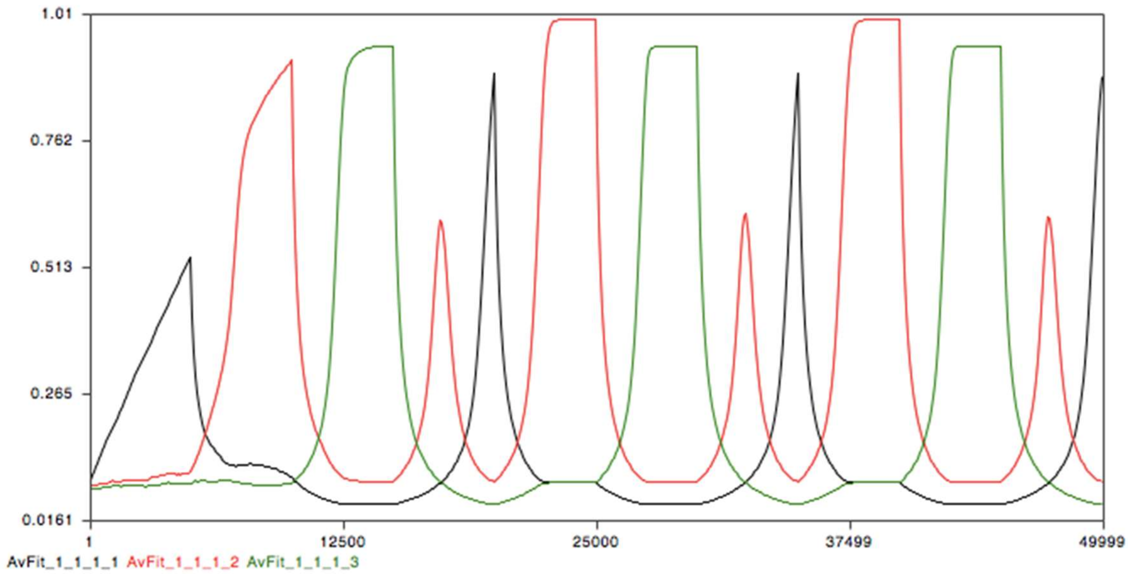

Figure 2: Group = 2, Interaction intensity aij = 0

For increasing level of intensity of interaction (Figure 3 and Figure 4), keeping the number of interacting technical characteristics Group = 2, we observe a similar pattern: a periodic unstable increase of the fitness of the technological dimension target of innovative activities from firms over time and an overall final improvement, although we do not observe a significative improvement of the fitness of the "mainstream" technological dimension. In particular, the periodical fitness improvement shows an instable behavior (as shown from the constant and cyclical increase and decrease of the lines), meaning that the fitness increasing due to the firms innovating on that technological dimension is not stable. A possible explanation for these results is that the intermediate intensity of interaction among technological characteristics combined with a low number of interacting technical characteristics (Group = 2) is not able to allow a stable increase of the fitness trough time.

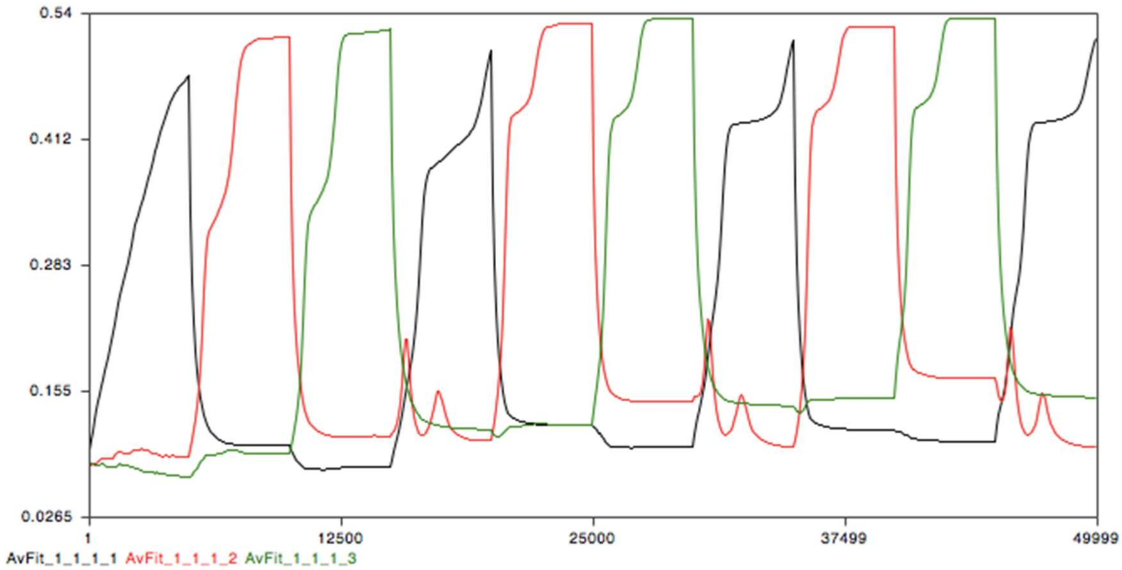

Figure 3: Group = 2, Interaction intensity aij = 0.5

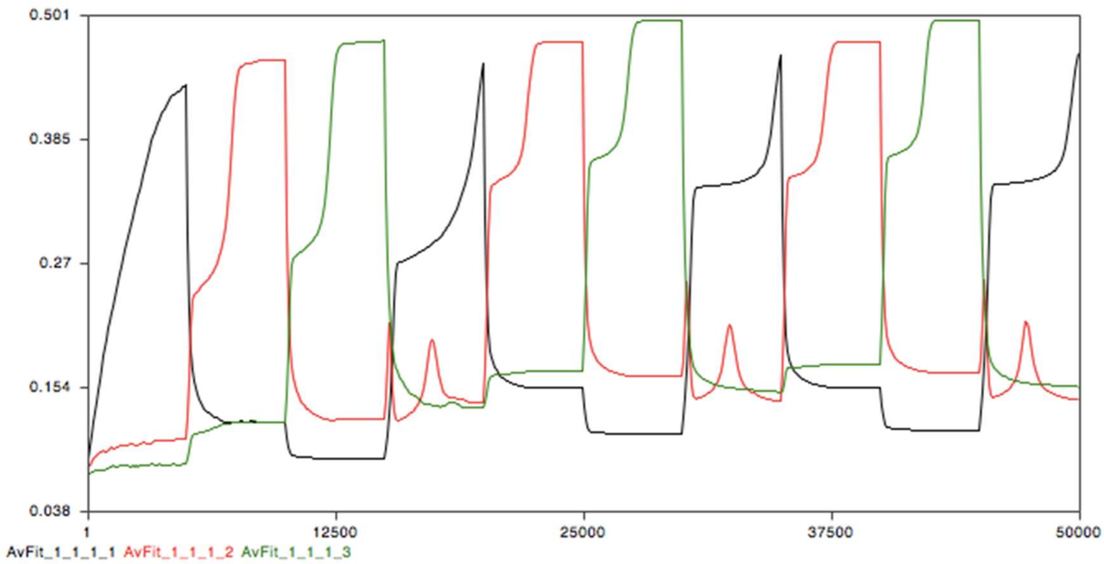

Figure 4: Group = 2, Intensity of interaction aij = 0.8

The results for the simulation run with the maximum interaction intensity level (aij = 1) and keeping the parameter Group = 2 show different results (Figure 5). We observe a progressive and stable increase of the fitness level of the three technological dimensions and a significant increase of the mainstream technological dimension fitness (although the gap between the increase of fitness of the black technological dimension at the initial time steps and the final steps of the simulation is minor). In addition, the behavior of the technological dimensions shows a cyclical trend, with a growing propensity of the green technological dimension. The reason why one of the frugal consumer's preferred technological dimension grows more than the other may be the fact that the green technological dimension is the last one the firms innovate on; therefore, it benefits more from the previous innovation efforts on the other two technological dimensions, and the effect is further exacerbated by the high intensity of interaction between technological dimensions.

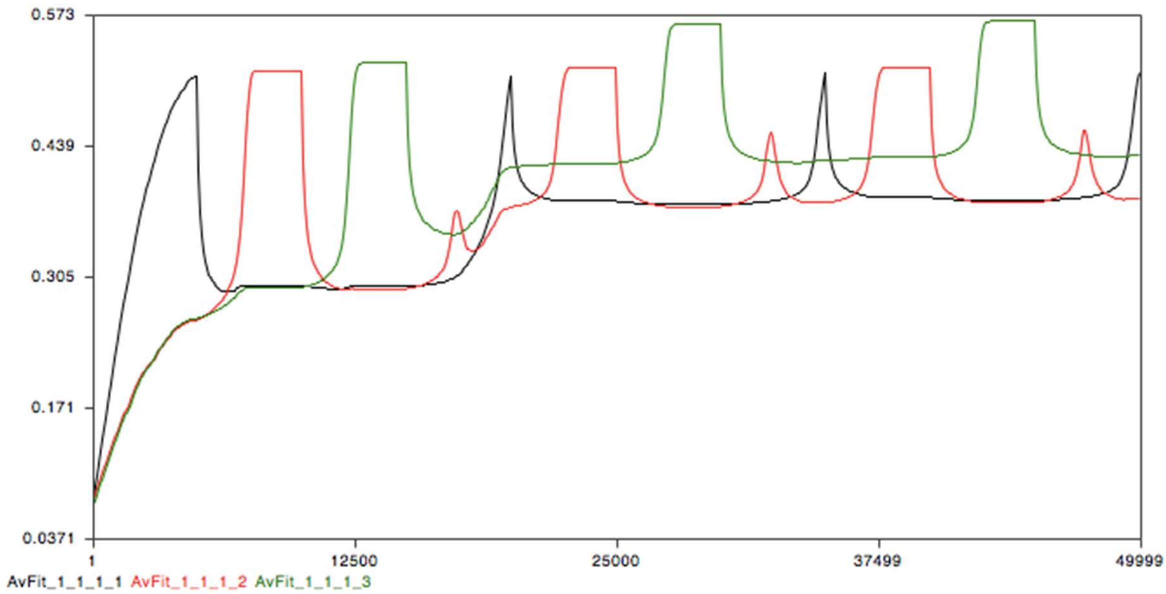

Figure 5: Group = 2, Intensity of interaction aij = 1

The second set of simulations (Figure 5 – Figure 8) shows different configurations of the parameter 'aij' keeping the parameter Group constant and equal to 8. The first simulation in Figure 5, with zero intensity of interaction and the number of interacting technical characteristics equal to 8 (out of a total of 12 technical dimensions) shows similar results of the simulation in Fig. 1, with Group = 2 and aij = 0, meaning that the effect of the parameter Group is null.

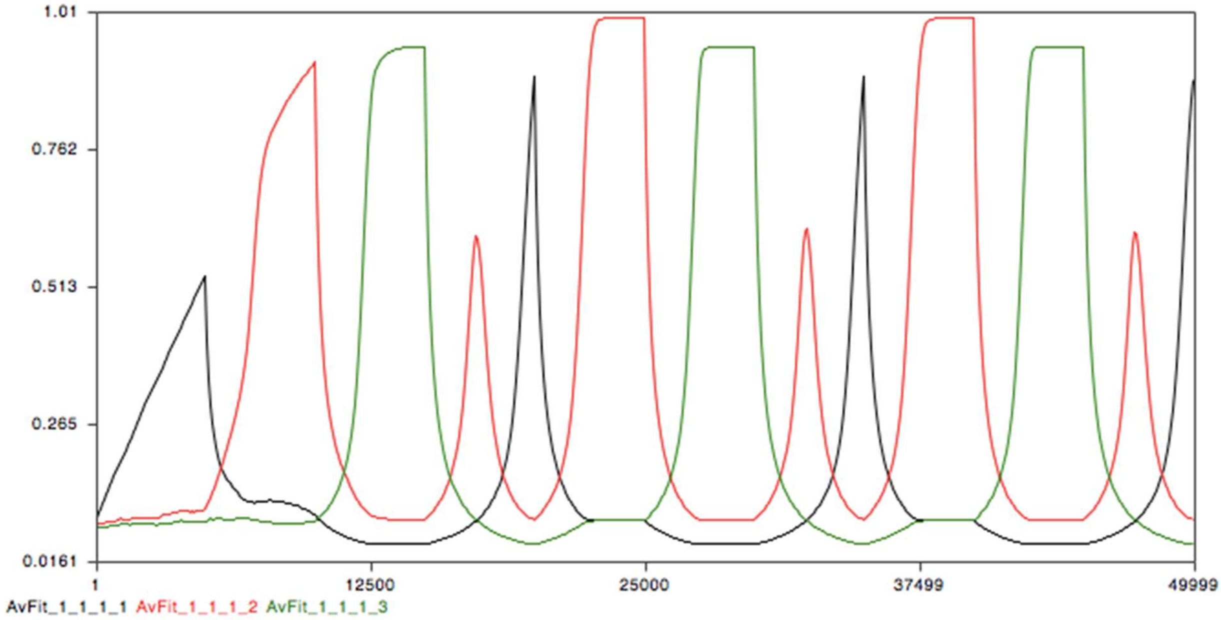

Figure 6: Group = 8, intensity of interaction aij = 0

The simulations in Figure 7 and Figure 8 shows the effects of intermediate interaction intensity (aij = 0.5 and aij = 0.8) and high number of interacting technological dimensions (Group = 8). The obtained results show an unexpected outcome. While the final fitness level increase of the mainstream technological dimension is unchanged in the two simulations, the increase over time of the all average fitness of the non-mainstream dimensions is higher when the intensity of interaction among dimensions is equal to 0.5, while we would expect higher intermediate improvement when the intensity of interaction is higher, i.e. when aij = 0.8.

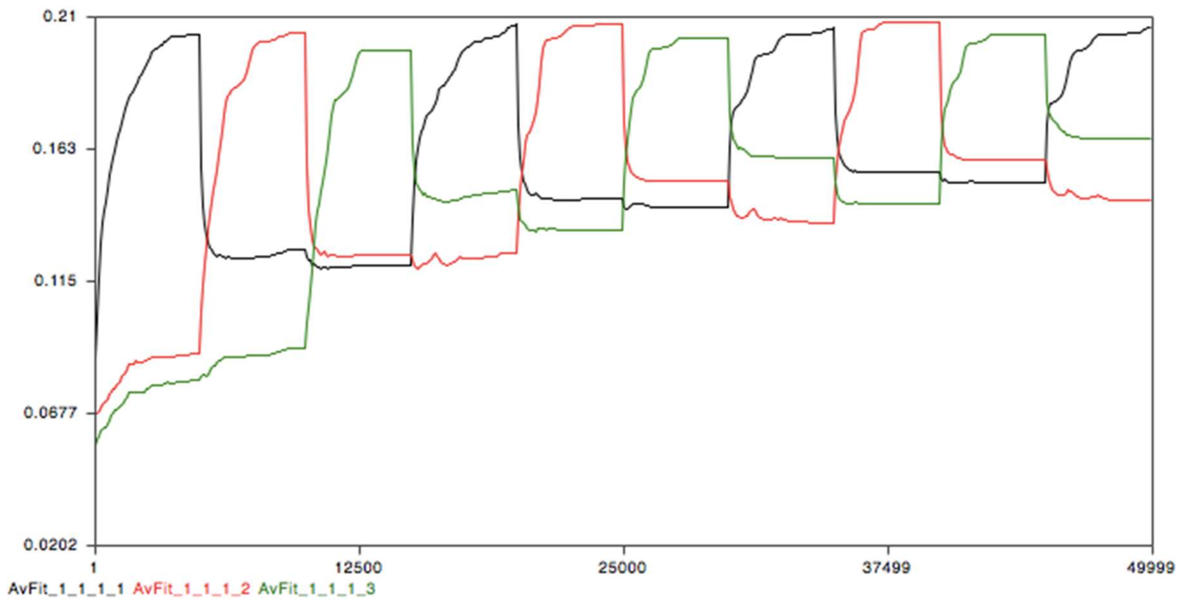

Figure 7: Group = 8, intensity of interaction aij = 0.5

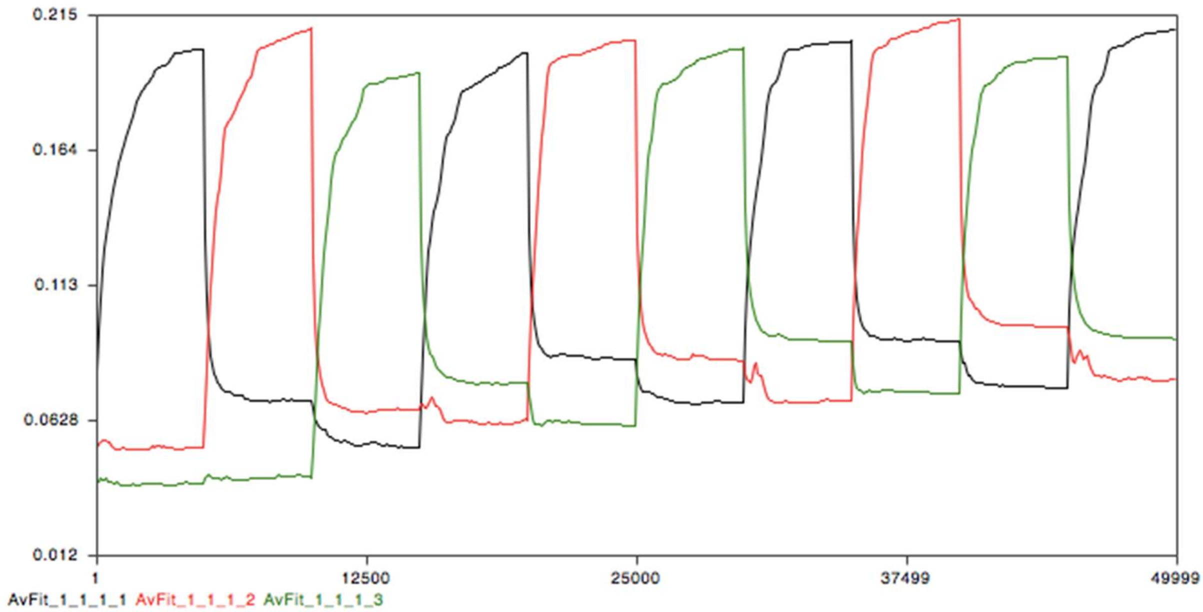

Figure 8: Group = 8, intensity of interaction aij = 0.8

The results of the simulation in Figure 9 shows a similar pattern, with Group = 8 and the maximum level of aij = 1 shows a peculiar outcome, resembling the case when aij = 0.8. This may lead to conclude that with high number of interacting technological dimension, a high intensity of interaction between technological dimension lead to a final improvement of the mainstream technological dimension, but an unstable increase of average fitness and thus performance in the intermediate steps, which may be expected in case of low intensity of interaction, but not in case of high intensity of interaction. These results may be due to a combined effect between the high number of interacting technological dimensions (Group = 8) and the excessive complexity caused by a high intensity of interaction between technological dimensions, which hinders the achievement of stable improvement of secondary technological dimensions. In fact, the highest and the most stable achievement of fitness improvement over time occurs when the parameter aij = 0.5, meaning that with high number of interacting technological dimensions (Group), a medium intensity of interaction among technological dimensions leads to more stable fitness and thus performance improvement on the mainstream dimensions.

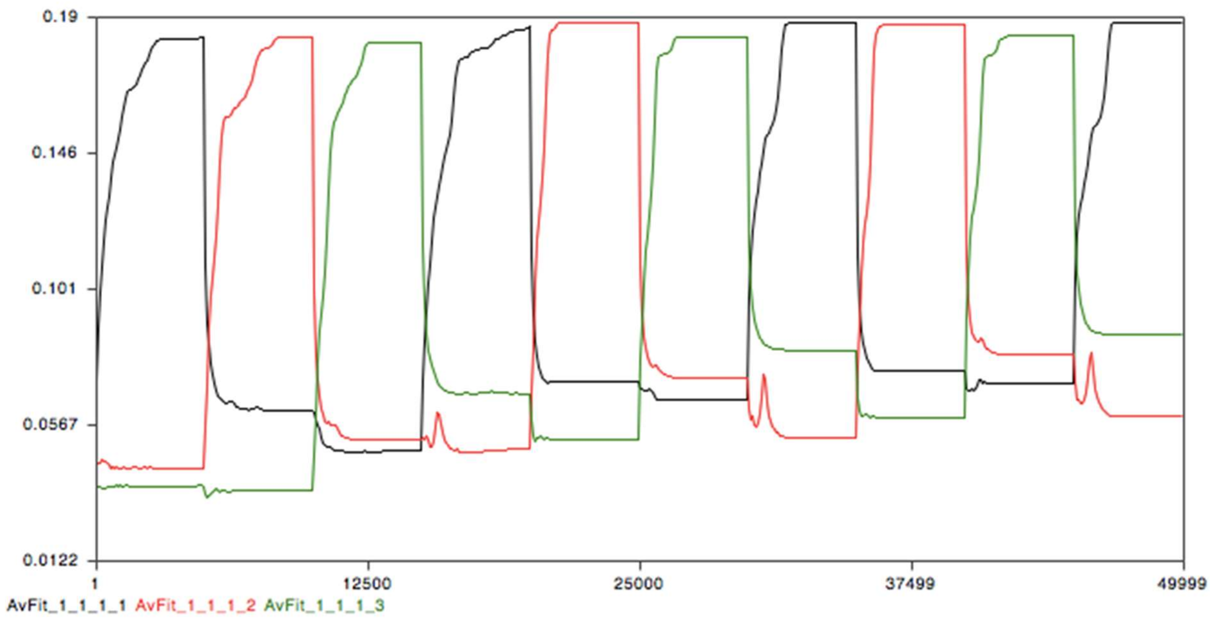

Figure 9: Group = 8, intensity of interaction aij = 1

It follows that firms that want to embrace the frugal innovation paradigm focusing on secondary technical characteristics, obtain a greater "design" architecture and performance improvement if the number of interacting technological dimension is low and the intensity of such interactions is very high, or whether the number of interacting technological dimension is high and the intensity of interaction among them is medium.

Discussion and conclusions

We adopt a product architecture perspective to observe and model the frugal innovation approach, as we believe that frugal innovation goes beyond the feature of product, process or business model innovation (Winterhalter *et al.*, 2017) and should be considered as an innovation paradigm. Our results show that significant fitness increase occur when the intensity of interaction between components is high and the number of components interacting is low, or when the intensity of interaction between components is medium and the number of component interacting is high, as showed in table 1. A multidimensional approach including product design and product architecture perspective would constitute a purposeful lens to analyze the results.

Table 1: summary of results

aij	K=2	K=8
0	null overall fitness increase	null fitness increase
0.5	small and stable fitness increase	significant and growing fitness increase
0.8	small and stable fitness increase	small growing fitness increase
1	significant increase	small growing fitness increase

We model the innovation search of firms pursuing frugal innovation strategy. The results show that frugal innovation, in terms of redesigning the architecture of existing products, leads to the improvement of the performance of all the technical characteristics. Indeed, this effect is affected by the architecture complexity and by the degree of interactions among functional elements of that product.

In this respect, we contribute to the growing literature of frugal innovation as architectural innovation providing theoretical evidence about how the performance of frugal innovations is affected by its architectural elements (which has been addressed by previous research to different extent). In fact, Ray and Ray (2010) analyzed the case of the C-DoT Indian telecommunication technology research center and how a simple architectural innovation has constituted a significant means to overcome structural barriers and to ensure good performance under scarcity condition despite reducing the product complexity and the technological sophistication. Lim and Fujimoto (2019) adopted a broader perspective in their attempt to develop a framework to characterize frugal innovation.

Previous studies addressed the reductive association of frugal innovation with poor, low-income contexts (Zeschky, Widenmayer and Gassmann, 2011; Altmann and Engberg, 2016; Hossain, Simula and Halme, 2016). Although its unquestionable fitting with low-end markets, this may hinder the adoption of frugal innovation as a standard practice or a valuable alternative to the more diffused, conventional approaches. Our results may constitute a stimulus to demonstrate, although only from a theoretical standpoint, the value of frugal innovation's outputs. The reason why even if the 'frugal' products work as the traditional ones we do not use them, is an interesting question which deserves a follow-up and constitutes a suggestion for future research avenues. A possible answer is the overall trend to associate any concept related to frugality and essentiality to negativity (Belk, 1985; Prabhu, 2017; Tiwari, Fischer and Kalogerakis, 2017) and to associate them to the concept of poverty and economic ascetism (Lastovicka *et al.*, 1999), along with the fear to be stigmatized by the society (Henry and Caldwell, 2006). The social pressure is in this context a key factor hindering the diffusion of frugal innovation approach, both from the consumers side and the supply side. The role of policy makers is crucial to circumvent the obstacles and to promote a different consumption and production paradigm, as well as fostering a broader understanding of the innovation process which includes changes in terms of society, infrastructures, markets, cultural values and consumption habits (Nocera, 2012; Rao, 2017; Mourtzis, 2018). These results cannot be achieved without a systematic transformation of the whole system of innovation, production and institutions, as well as university and research center, that should be encouraged more in doing research in frugal innovation area, finding new way to revise existing product architecture in order to craft innovative, no-frills solutions.

The lessons from the experiment are highly relevant for innovative managers which seeks for an alternative approach to innovation. In addition, it stimulates R&D managers and engineers to adopt a different mindset in product design and innovation process, to reconfigure components exploiting the deep knowledge about old downgraded technologies and to find different solutions to tackle complex problem. In fact, the new product architecture design based on frugal innovation approach could further create a new knowledge base a new technological competence domain and will prompt the experimenting of new product architecture which might be superior than the established ones and that would not be otherwise experimented. From a patent activity standpoint, the new innovation approach could solve the issue of decreasing growth rate trend of patent application (WIPO, 2019) experienced since 2012.

In this regard, further avenues of research could address the issue of how frugal innovation relates with patent activity issues, which percentage of frugal innovations turns into patent applications and granted patents and eventually the most frequently featured technological field. To the best of our knowledge, little attention has been devoted to the analysis of the frugal innovation production analyzing the patent activities (Howell, van Beers and Doorn, 2018; Krishnan and Prashantham, 2019).

It is important to stress some caveats to our analysis. First, the NK model itself has several limitations: the search space and its parameter are considered exogenous and there is no control over the evolution and reconfiguration of the search space occurring after explorations. Second, although the model allows to parametrize the firms' search behavior which is assumed to reflect the firm's innovation strategy, it does not allow any sort of agents' (in this case firms) heterogeneity in terms of other elements (size, technological level etc.). Third, the lack of control on the K parameter: in our case, we can set the number of interacting components, but we have no control over which component interacts with whom. In addition, we assume that each component interacts with the others, excluding the possibility of a component within the K interacting which interact with only one component. Last, the agent-based modelling approach, although accounts for complex interactions of multiple interdependent processes and the emergent properties of the system (Harrison *et al.*, 2007), encompasses a subtle generalizability of results and the following theorization. Generalizations should be at best be considered conjectures, while inferences based on the simulated experiments results should be considered as hypotheses.

We acknowledge the need of additional experimental set up to obtain additional results, e.g. exploring different configuration of the parameters 'aij' and 'Group'. In this way we could obtain deeper insights about the effect on average fitness and frugal innovation performance of the complexity of the interactions among technical characteristics, and the thresholds under which those innovations could be considered as "underperforming". However, we provided initial insights to enrich the analysis and a possible direction for future avenues. We advance the idea that a different perspective towards frugal innovation which capture the technical and design shades of the phenomenon constitutes a promising area to trigger future diffusion.

Appendix

Sensitivity Analysis

The tradeoff between representability and complexity has experienced a long debate in the agent-based modelling literature, as powerful models are those able to represent the reality as closest as possible, thus resulting in increasing complexity and in a high number of parameters. The choice of the parameters to vary in the simulation experiments, the parameter "aij" in this work, the parameter "Group" in the previous chapter, may be considered an arbitrary choice for the purpose of the research. However, the literature provides analytical tools to validate the "relevance" of specific parameters over the others as the sensitivity analysis (SA) (Saltelli et al., 2008).

The general purpose of the sensitivity analysis is "studying how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input" (Saltelli et al., 2004:45). The general definition of sensitivity analysis accounts for the understanding of which are the model parameters more involved in the changes in the model output. Translating the definition to the agent-based modelling scenario, sensitivity analysis identifies the parameter or set of parameters that are the main responsible of the variance of the model output, eventually in getting rid of non-relevant parameters (Saltelli et al, 2004).

Among the various quantitative methods to conduct a sensitivity analysis, we relied on the variance based Sobol's method (Sobol', 1993), which is one of the most powerful technique to ascertain how much a model depends on each or some of its input parameters (Chan, Saltelli, and Tarantola, 1997). In general, variance-based sensitivity analysis methods compute the amount of variance of the model's output generated by the single parameter and/or the interaction of two or more parameters (Sobol' sensitivity indices).

Sobol Sensitivity Analysis

The Sobol' sensitivity analysis approach (Sobol', 1993) is method based on the variance decomposition. It can handle integrable function, which can be decomposed into summands of different dimensions, and it rely also on the Monte Carlo algorithm to estimate the sensitivity of a function with respect to arbitrary group of variables (Nossent, Elsen, and Bauwens, 2011). Let us suppose that the model is represented by the function (4),

$$Y = \mathrm{f}(x) = \mathrm{f}(x_1 \ldots . x_p) \quad (4)$$

where Y is the model output, and x = $(x_1 \ldots x_p)$ are the parameters. The function can be represented also as an expansion into summands of different dimensions, as in (5):

$$\mathrm{f}(x_1 \ldots . x_p) = f_0 + \sum_{i=1}^{p} f_i\,(X_i) + \sum_{i=1}^{p} \sum_{j=i+1}^{p} f_{ij}\,(X_i, X_j) + \ldots + \mathrm{f}\,i_{1 \ldots\ldots p}\,(X_{1,} \ldots X_p) \quad (5),$$

where the terms of the decomposition represent the combined effect of single, couple, triad of parameters etc.

Sobol'(Sobol', 1990) demonstrated that under the condition that f_0 is constant and the integrals of the summands $\mathrm{f}\,i_{1 \ldots\ldots i}$ with respect to their own variables are zero as shown in (6), and all the summands are orthogonal, there is a unique expansion of (x) for any function $\mathrm{f}(x)$, and the decomposition (6), also called ANOVA-representation of f(x) (Sobol, 2001), is unique as in (6):

$$\int_0^1 \mathrm{f}\,i_{1 \ldots\ldots ip}\,(x_{i1}, \ldots, x_{ip}) dx_k = 0 \;\; for\; k = i_1, \ldots, i_p \quad (6)$$

The total unconditional variance can be defined as in (7) (note that the integral is defined in the range between 0 and 1, representing the parameter range):

$$\mathrm{V}(Y) = \int_0^1 f^2(X) dX - f_0^2 \quad (7)$$

The partial variance, computed from the total variance decomposition, is computed from (5) squaring both sides of (5) and integrating results, having the condition in (6) satisfied.

$$V_{i_1 \ldots i_s} = \int_0^1 \ldots \int_0^1 f_{i_1 \ldots i_s}^2\,(X_{i_1, \ldots,} X_{i_s}) dX_{i_1} \ldots dX_{i_s} \quad (8)$$

where $1 \leq i_1 \leq \cdots \leq i_s \leq p$, and $s = 1, \ldots, . p$.

This results in Eq. 9 for the variance decomposition.

$$V(Y) = \sum_{i=1}^{p} V_i + \sum_{i=1}^{p-1} \sum_{j=i+1}^{p} V_{ij} + V_{1,\ldots,p} \quad (9)$$

The general formula in (10) provides the global sensitivity indices:

$$S_{i_1 \ldots i_s} = \frac{V_{i_1 \ldots i_s}}{V} \quad (10)$$

The integer *S* is often called order of dimension of the index (7). All the $S_{i_1 \ldots i_s}$ are nonnegative and their sum is 1 (Sobol, 2001).

The higher the sensitivity indices value, the more influential the respective parameters are. The large, computational power that the sensitivity indices computation requires (due to the integral calculus to compute the variance), has led to the adoption of Monte Carlo simulation algorithm to run a meta-modelling estimation of the variance (Homma and Saltelli, 1996; Nossent et al., 2011; Sobol', 1993). The Monte Carlo method is suitable in the specific class of numerical integration problems (Kroese, Brereton, Taimre, and Botev, 2014) and it is based on the repeated random resampling to estimate unknown parameters.

Therefore, the estimation of the total unconditional variance defined in (7) becomes:

$$\hat{V}(Y) = \frac{1}{n-1} \sum_{m=1}^{n} f^2 (X_m) - \hat{f}_0^2 \quad (14)$$

with X_m is a "resampled" set of input parameters and *n* stands for the number of samples. As the *n* increase, the estimation becomes more accurate.

Sobol' sensitivity analysis of Alternative Innovation pNK model

In a global sensitivity analysis, all parameters are varied simultaneously over the entire parameter space, which allows to simultaneously evaluate the relative contributions of each individual parameter to the model output variance. The Table 1 shows the selected parameter space to perform the experiments in the sensitivity analysis (note that the referred parameter space and experiments have nothing to do with the experiments run as main analysis but are repeated experiments over a parameter range for the specific purpose of the sensitivity analysis). The results of the Sobol' decomposition in Figure 10 shows the Sobol' sensitivity indices of five parameters (Group, aij, beta, Xc, app). The Sobol' sensitivity analysis algorithm requires to select a sample of model parameters to include in the analysis (all the model parameters can be included).

The Table 2 shows the Sobol' decomposition of the five parameters analyzed. It shows that the main effect is higher for the parameter 'Group' and 'aij', while is not significant for the parameter 'Beta', 'Xc' and 'app' (although the literature has never defined any cutoff value, the common accepted threshold is 0.05). The interaction effect is not significant, being approximately equal to zero. The graph in Figure 10 shows the main effect, i.e. the total order sensitivity indices of the five parameters. The greater the sensitivity indices, the more relevant the parameters are in respect to the model output. The graph shows that the parameters 'Group' and 'aij' have the higher sensitivity indices, meaning that they strongly contribute to the model output, and thus they are the relevant parameters to investigate in the simulation experiments. In fact, as mentioned above, the Sobol' sensitivity analysis tests the influence of each parameters over the model output (Saltelli, Tarantola, and Campolongo, 2000) and enables to identify the relevant parameters which contribute the most to the model output variance, showing that the relevant parameters to vary are 'Group' (see. Chapter 2) and 'aij'.

Considering the two dominant parameters detected by the Sobol' decomposition, Figure 11 and Figure 12 shows the meta-model responses respectively for parameter 'aij' and for parameter 'Group', obtained with a Kriging meta-modelling estimation. The Kriging meta-modelling estimates a 'meta-model' of the baseline underlying simulation model, which is a simpler mathematical function that approximates the implicit function (Kleijnen, 2009). The Kriging meta-model is expressed as in (15):

$$Y\mathbb{x} = \lambda\mathbb{x} + \delta\mathbb{x} \qquad (15)$$

where $\mathbb{x}$ is a vector representing the point in the parameter space, and $\lambda\, \mathbb{x}$ is the function which represents the global trend of the meta-model Y, as in (16):

$$\lambda\, \mathbb{x} = \sum_{i=1}^{l} \beta_i\, f_i(\mathbb{x}), \text{ con } l \leq 1. \quad (16)$$

with $f_i(\mathbb{x})$ being a fixed arbitrary function and β_i is the coefficient to be estimated from the sampled response of the original model. In (15), $\delta\, \mathbb{x}$ represents the stochastic process deviating from the global trend.

Kriging predicts the response of unobserved points i.e., those whose response has not been obtained by the simulation based on all of the observed points (Li, Li, and Azarm, 2008). The estimation requires a repeated simulation (we run 17 simulations) to obtain a meta-model which best fits our model. As multiple simulations to estimate the meta-model were conducted we follow Dosi et al. (2018) to select the best trend and correlation functions, and we perform an evaluation of the goodness-of-fit based on cross (in-sample) and external (out-sample) validation (Salle and Yıldızoğlu, 2014). The cross validation is conducted using the Q^2 statistic (a proxy of the R^2), while the external validation is conducted on the root mean square error (RMSE) measure; to estimate the meta-model, we selected the function pair best fitting in respect to both the criteria. In Table 3, the Q^2 and the external RMSE show a good general meta-modelling fitting, with $Q^2 = 0.697$ and $RMSE = 0.004$ (the higher the Q^2, in a 0-1 interval, the better, while the 'lower' the value of RMSE, the better).

The results show that the model output 'AvFit' (average fitness) is more sensitive to a variation of the parameter 'aij' (Figure 11) than the parameter 'Group' (Figure 12). In addition, the results show also a linear trend between the parameters and the model output AvFit.

Table 1: Experimental parameter space

PARAMETERS RANGE
Group: 1 - 12
aij: 0 - 1
Xc: 0 - 0.5
beta: 0 - 0.5
app: 0 – 0.5

Table 2: Sobol decomposition sensitivity analysis

	Main Effect	**Interaction**
Group	0.3272	0.0007619
aij	0.661	0.001531
beta	0.001065	5.943e−05
Xc	0.007324	6.933e−05
app	0.0009922	4.714e−05

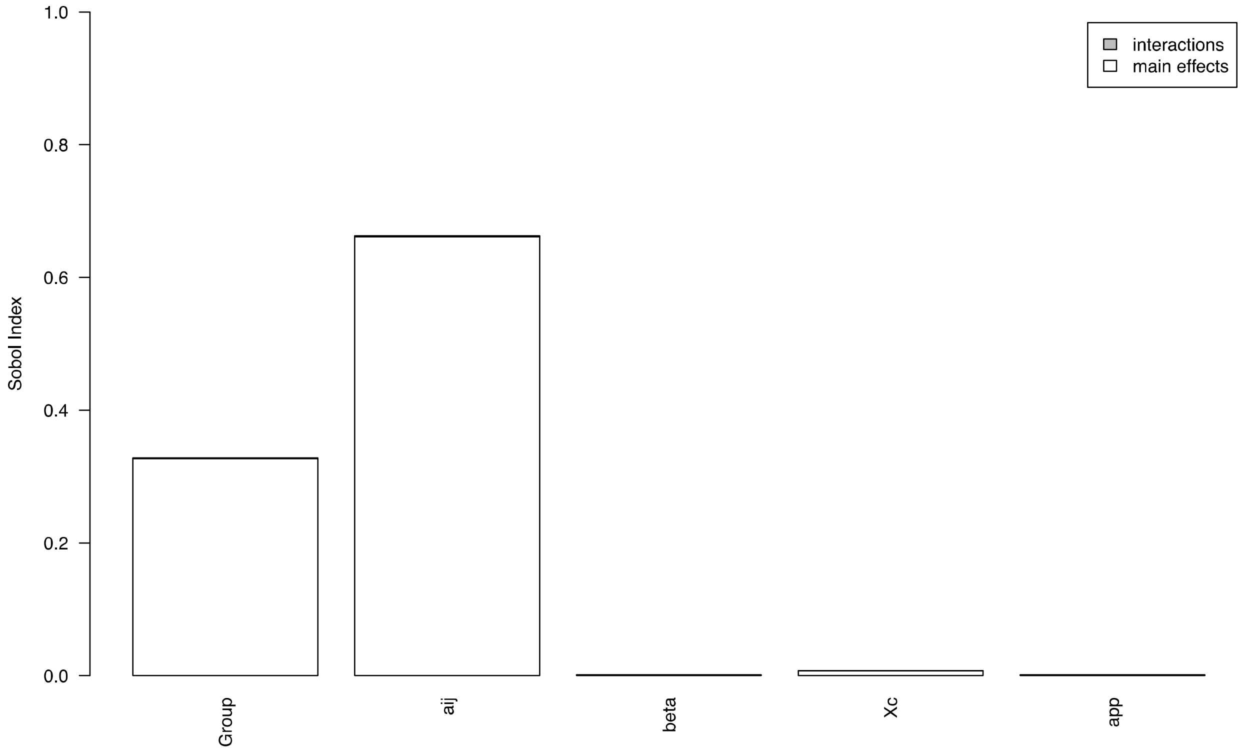

Figure 10: Sobol' decomposition sensitivity analysis

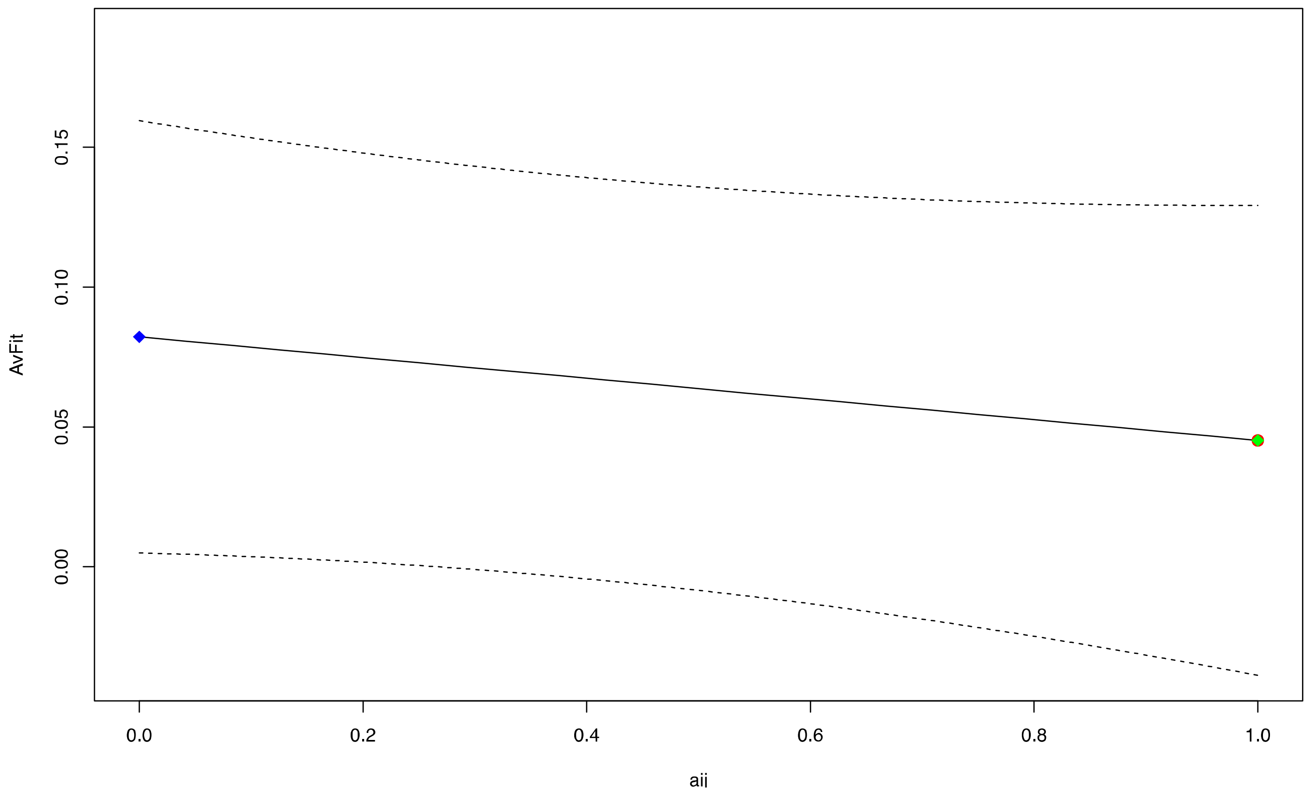

Figure 11: Meta-model response for parameter 'aij'

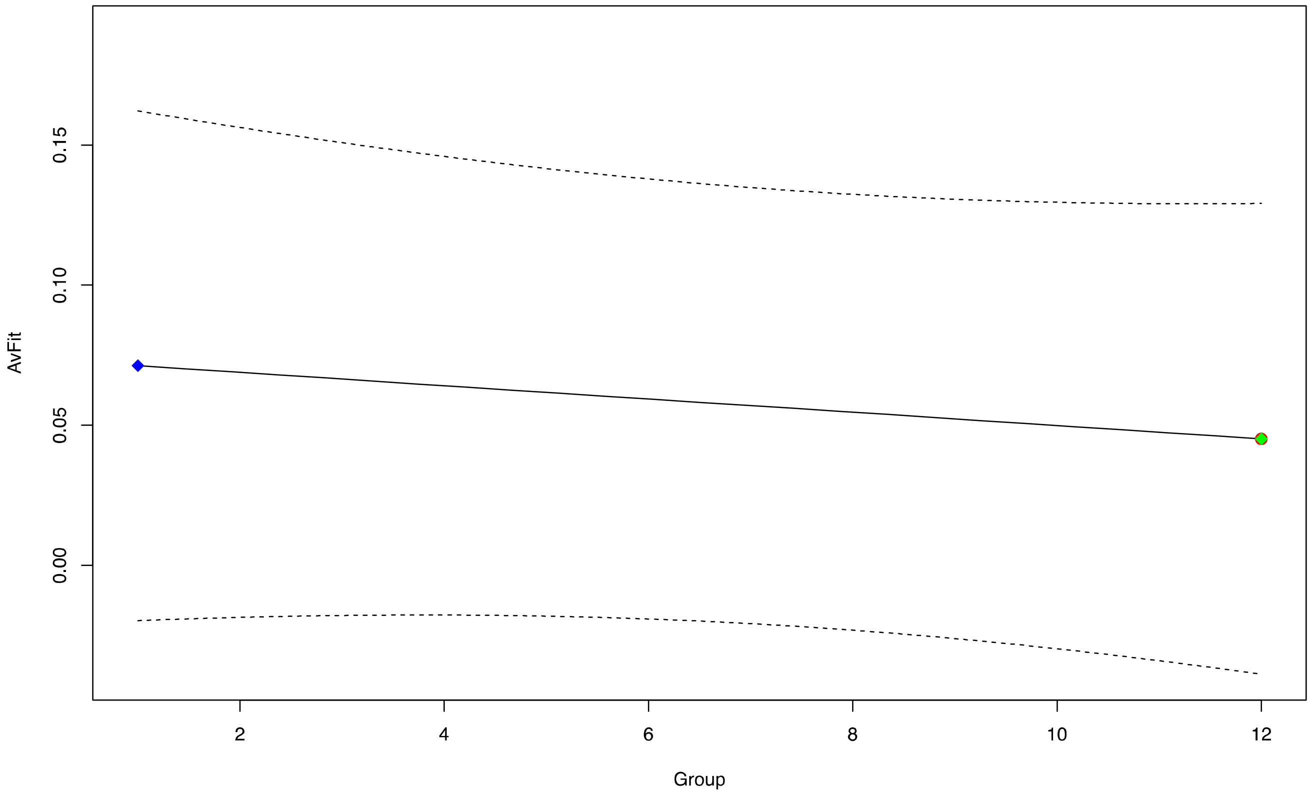

Figure 12: Meta-model response for parameter 'Group'

Table 3: Comparison of alternative Kriging models (Q2 higher is better; RMSE lower is better)

	Matern 5/2	**Matern 3/2**	**Gaussian**	**Exponent.**	**Power exp.**
Q2 constant trend	0.945	0.915	0.964	0.594	0.949
Q2 1st order polynomial trend	0.647	0.686	0.647	0.647	0.697
RMSE constant trend	0.017	0.017	0.017	0.017	0.017
RMSE 1st order poly. trend	0.003	0.003	0.003	0.003	0.003
MAE constant trend	0.015	0.015	0.015	0.015	0.015
MAE 1st order poly. trend	0.003	0.003	0.003	0.003	0.003
RMA constant trend	1.97	1.97	1.97	1.97	1.97
RMA 1st order poly. trend	0.369	0.369	0.369	0.369	0.369

Table 4: Kriging meta-model estimation (standardized)

λ(intercept)	0.108	**Correlation function**	Power exp
Trend (inclination)	-0.026	**Cross-sample Q^2**	0.697
ψ(Group)	1.277	**External RMSE**	0.004
ψ(aij)	1.906	**External MAE**	0.003
ψ(beta)	0.488	**External RMA**	0.369

ψ(Xc)	0.948	**DoE samples**	17
ψ(app)	1.185	**External sample**	10
Trend specification	1^{st} order poly.		

Conclusions

Research on frugal innovation is mostly concerned with the identification of strategic challenges that could hinder the frugal innovation activities in firms' strategic plan and how frugal innovation can be addressed to meet social and sustainable goals and the most promising industrial applications. Most of this research has been conducted out of the confines of the dominant paradigm of innovations, considering frugal innovation activity as a low-end alternative to the traditional, sophisticated innovations from western countries. This dissertation suggests that frugal innovation may constitute an alternative that coexists next to the dominant innovation paradigm rather than contrasting with it. In addition, it may be representing a way to escape from the saturation point of the current technological trajectories.

This work provides a multidimensional framework for supporting ground-breaking research on frugal innovation: apart from our attempt to provide the missing link between the concept of frugal innovation and the product architecture literature, this work seeks to encourage an observation from additional angles, such as technology reemergence, technology cycles, market redefinition, and industry evolution.

We acknowledge that a more consistent availability of empirical data would help to advance the state of research, and that such scarcity represents indeed an obstacle to obtain more consistent results which would pave the way for other researches.

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