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What pathways lead to frugal innovation? Some insights on modes & routines of frugal, technical inventions based on an analysis of patent data in German auto components industry

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What pathways lead to frugal innovation? Some insights on modes & routines of frugal, technical inventions based on an analysis of patent data in German auto components industry

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Abstract

Frugal innovations, i.e. affordable products and services with appropriately good quality, are getting increasingly important for securing long-term competitiveness in both, the developing world and in industry nations. Nevertheless, ensuring actual implementation of technology-driven frugal inventions remains an under-researched area. This study investigates modes and routines employed by techno-entrepreneurs from industry nations when innovating frugally. The study is based on the patent data of seven auto component sector firms from Germany with a documented history of contributing cost-effective solutions to frugal vehicles. With the help of a keyword analysis we identify the role of frugality in (patented) technical inventions. Select case studies of frugal inventions show that cost effectiveness and environmental sustainability can be often achieved by simplification of design and production process, as well as by eliminating avoidable complexity, e.g. through standardization. The study shows that frugal inventions in the investigated firms are often driven by individual inventors, while potentials of open global innovation networks are under-utilized. Furthermore, the study shows that frugality can (only) be achieved by a holistic approach that encompasses the entire value chain, including logistics and waste management. The results are potentially beneficial for techno-entrepreneurs across industry sectors and product domains.

Keywords: Frugal Innovation; Techno-entrepreneurship; Frugal Invention; Patent Analysis; Auto Components; Germany; Simplification

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1. Introduction

The concept of "frugal innovations" has established itself in the scholarly discourse as well as in business practice (cf. Radjou and Prabhu, 2015; Weyrauch and Herstatt, 2016). Development of affordable products and services for resource-constrained, price-sensitive customers has been often addressed by various names, such as "Jugaad", "grassroots innovations" or "Base of the Pyramid", to cite but a few examples (Prahalad, 2004; Radjou *et al*, 2012; Gupta, 2016; Tiwari *et al*, 2017). More recently, scholars have started to take a rather nuanced approach acknowledging the differences in the core ideas of these individual concepts despite a certain and undeniable overlap (Zeschky *et al*, 2014; Tiwari *et al*, 2016).

A consensus seems to have emerged around the perception that frugal innovations usually refer to those innovative products, services or processes, which enable a significant reduction in the total cost of ownership/usage while ensuring adherence to relevant safety and regulatory norms (Tiwari and Kalogerakis, 2016). With this value proposition, frugal innovations often reach out to unserved customer groups while ensuring "affordable excellence" (Tiwari and Herstatt, 2012b). For example, the managing director of a large and successful German auto component supplier in India was quoted as saying that for succeeding in India one needs "a product which costs 30% of the global price and offers 95% of the performance" (Tiwari and Herstatt, 2014: 6). Various experts have called upon firms to create frugal products and services (Zweck *et al*, 2017). A recent study by Ray and Miglani (2018) discusses the role of frugal innovations in the technology upgrading in India's automobile industry and thereby underscores the role of frugality in the long-term competitiveness of techno-entrepreneurs. Firms themselves, too, have recognized such opportunities, as is evident from the following statement in the Annual Report of Germany's Bosch Group (2017: 29-30): "There is demand for affordable products that often have to meet special requirements of the local market, such as robustness and ease of repair."

Traditionally, scholars have connected frugal innovations to emerging economies (Zeschky *et al*, 2011; Agarwal and Brem, 2012; Tiwari and Herstatt, 2012a; Tiwari and Kalogerakis, 2016). Many of such innovations, however, have found successful diffusion in the advanced economies of industry nations (Immelt *et al*, 2009). Some scholars have termed this flow of innovations from the global South to the global North as "reverse innovations" (Agarwal and Brem, 2012; Govindarajan and Trimble, 2012; Von Zedtwitz *et al*, 2015), while others have explained it with the concept of "lead markets" (Herstatt *et al*, 2008; Tiwari and Herstatt, 2012a; Jänicke, 2014; Quitzow, 2015). Nevertheless, recent studies emphasize the need for companies from the industrialized world to engage in frugal innovations. This is, on one hand, motivated by the desire to retain global competitiveness in the face of increasing importance of price-sensitive markets in emerging economies. On the other hand, inwards foreign direct investments (FDI) by firms from emerging economies have also intensified price-driven competition in industry nations (Kroll *et al*, 2016; Herstatt *et al*, 2017).

However, the modes and routines of product development concerning frugal innovations remain under-researched. Since frugal innovations are a relatively nascent phenomenon, much scholarly attention has been paid to comprehending the "what" and "why" aspects rooted in the realm of strategic management (Tiwari and Kalogerakis, 2016). Operational issues, such as the actual process of product development, have received relatively less scholarly attention with few notable exceptions. For example, Lehner and Gausemeier (2016) have analysed 29 frugal innovations and identified a pattern system for "problem categories" leading to realization of frugal solutions. Rao (2017), on the basis of 25 cases of frugal innovations, has proposed

principles of frugal design and frugal engineering for robust, affordable and environmentally sustainable products. More recently, Tiwari and Kalogerakis (2017) have attempted to identify innovation pathways and trajectories leading to frugal solutions in India's auto component industry, while Bergmann and Tiwari (2017) have investigated innovation pathways in the German auto component sector. Ramdorai and Herstatt (2015) have analysed organizational factors by domestic and foreign-owned, large firms in India as enablers of frugal solutions in the healthcare sector.

Despite such above-mentioned efforts, so far, the modes and routines employed in research and development (R&D) by frugally-innovating techno-entrepreneurs operating in the context of industry nations has remained under-researched. This research gap is especially intriguing because the contribution of such techno-entrepreneurs especially in the less visible business-to-business (B2B) segment of the auto component industry in creating frugal solutions is well documented (cf. Bhargava and Seetha, 2010; Tiwari and Kalogerakis, 2017).

The present, explorative study intends to address this research gap by generating preliminary insights with the help of a patent analysis that is performed on selected techno-entrepreneurs with a documented history of participating in the development of frugal vehicles. The analysis shows that these techno-entrepreneurs, at least occasionally, engage in frugal inventions that help to reduce costs significantly while adhering to safety standards and ensuring technological progress. The modes and routines that the investigated firms apply in creating those frugal inventions encompass the complete value chain – consumption of energy and material is sought to be reduced, re-use of material is promoted and manufacturing processes are simplified, to name but a few examples.

The remained of this chapter is structured along the following lines: the concept of frugal innovation and its relevance for techno-entrepreneurs are discussed in section 2. This section also showcases how Germany-based auto-components suppliers have contributed to their development by enabling frugal components and technologies. Section 3 builds the cornerstone of the study. It contains results of a patent and keywords analysis of the selected companies to identify what role, if any, frugality plays in such technical inventions and what aspects are of particular importance to these techno-entrepreneurs. Furthermore, section 4 presents some particularly interesting patents that help characterize the frugality of the patented inventions and the modes and routines utilized in them. The chapter concludes with a summarizing discussion in section 5.

2. Frugal innovation for techno-entrepreneurs

2.1. Theoretical foundations

Frugal innovations in the past have been subject to differing opinions amongst scholars and have been often connected to emerging economies. It is only recently that a growing number of scholars have started to emancipate frugal innovations from the overly strong regional and/or market boundaries. As an analysis of the scholarly discourse (Tiwari and Kalogerakis, 2016) has revealed, there is an emerging consensus that frugal innovations are targeted at *price-sensitive* customers, and not exclusively at "the poor" as such. Firms can take recourse o frugal products and services in any part of the world to secure competitive positions. Frugal solutions can also ensure social welfare with sustainable development and fair access to basic societal

needs such as healthcare, education and mobility (Leadbeater, 2014; Rosca *et al*, 2016). We define frugal innovation, adapted from Tiwari and Herstatt's (2017) propositions, as follows:

> Frugal innovations refer to those innovative products, services or processes which seek to create attractive value propositions for their targeted customer groups by focusing on core functionalities and thus minimizing the use of material and financial resources in the complete value chain. They substantially reduce the cost of usage and/or ownership while complying with all relevant regulatory norms governing quality and safety. At the same time, they may seek to disrupt prevailing industry standards set by established incumbent firms.

A core feature of this extended definition is that it explicitly emphasizes the possible disruption of prevailing industry standards in product architecture and technical features, while innovative solutions remain compliant to regulatory norms and standards.

Frugal products have been associated in the academic literature with substantial cost-reductions, high affordability, robustness, user-friendliness, economies of scale and attractive value proposition (Rao, 2013; Tiwari and Herstatt, 2014). Weyrauch and Herstatt (2016) have defined them with substantial cost reductions, focus on core functionalities and performance optimization in direct relation to the context-specific needs. In a prior study (cf. Bergmann and Tiwari, 2016) we have analysed the German media discourse on frugal innovation with the intention to analyse its visibility, acceptance and perception in the society. The study showed that this topic has been gaining momentum since 2013 with increasing visibility and acceptance. A keyword-analysis, performed on 108 non-academic, online articles published between 2010 and 2015 in the German-language media, showed that frugal products are perceived to be functional, resource-efficient, user-friendly and affordable. In addition, they are thought to ensure simplification by reducing unnecessary complexity and as offering new growth opportunities (Bergmann and Tiwari, 2016). This understanding of frugal solutions builds the base for the present study, see Figure 1.

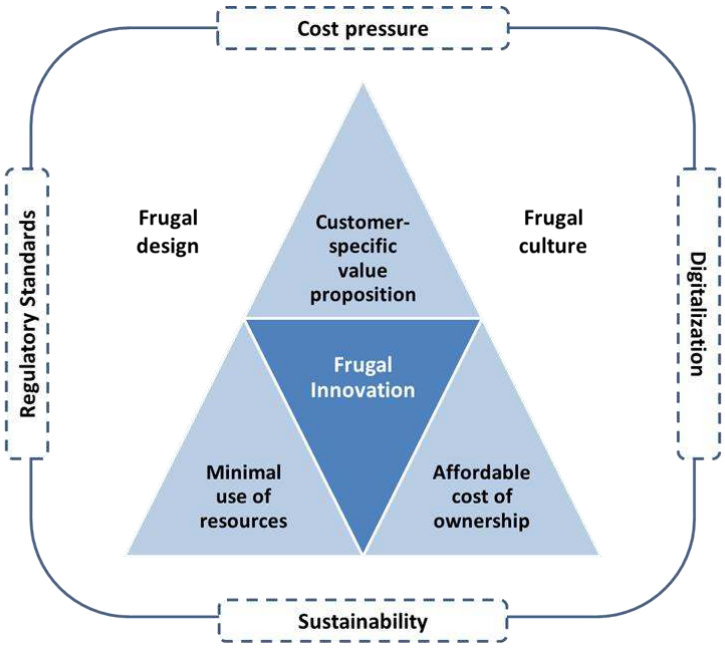

Figure 1: A reference model for frugal innovations[1]

[1] Adapted from Kalogerakis *et al* (2017: 14)

As depicted in Figure 1, frugal innovations tend to strive for an affordable cost of ownership, minimize the use of resources and provide a customer-specific value proposition. To provide these features the innovating firms must attempt to create frugal designs and should have a corporate culture that not only accepts but also promotes frugality.[2] The firms are encouraged to innovate frugally by (a) the changing and more stringent regulatory standards that seek to enhance resource efficiency, (b) increased cost pressure, e.g. due to intensifying competition and due to prevailing demand conditions in unsaturated, growing markets in the emerging market economies, (c) opportunities of digital transformation that provide cutting-edge technologies for product development and commercialization while significantly reducing costs and enhancing quality, and finally (d) growing societal concerns for sustainability (Kalogerakis *et al*, 2017). This framework provides a basis for the modes and routines that lead to creation of frugal products and services.

Technology entrepreneurship can be understood as "a style of business leadership that involves identifying high-potential, technology-intensive commercial opportunities, gathering resources such as talent and capital, and managing rapid growth and significant risks using principled decision-making skills" (Byers *et al*, 2011: xv). Following this, techno-entrepreneurs can be regarded as any individuals or organizations introducing novel products or services to the market. According to Blanco (2007: 3), techno-entrepreneurs "aim at creating and capturing economic value through the exploration and exploitation of new technology-based solutions". For opportunity recognition and exploitation they must be able "to match current and future technologies, market needs and resources in a vision of a future business opportunity" (Blanco, 2007: 3).

Figure 2: Drivers for frugality for techno-entrepreneurs

With increasing globalization techno-entrepreneurs have to compete in a global world and the importance of "emerging market and developing economies" (EMDE)[3] has increased tremendously. The share of EMDE in the global economic output, in market prices, stood at 20.8% at the turn of the millennium in 2000 and is estimated to have almost doubled to 39.9%

[2] A recent literature review conducted by Krohn and Herstatt (2018) also underlines the role of a frugal "mind-set" in the successful development of frugal solutions.

[3] International Monetary Fund (IMF) categorizes worldwide 39 countries as "advanced economies" and 153 countries as "emerging market and developing economies" (cf. IMF, 2017).

by 2017. By 2022, it is forecasted to cross the mark of 44% (IMF, 2017). The growth is even more impressive in absolute numbers: while the cumulative gross domestic product (GDP) of the EMDE nations stood at $7 trillion in 2000, it is estimated to have grown more than four-times to $31 trillion by 2017 and is forecasted to cross $44 trillion by 2022. It is, therefore, but natural that frugal products, services and technologies that can enable access to vast and growing middle-classes in EMDE, play a key role in the world of techno-entrepreneurship. Figure 2 summarises these core drivers of frugality for techno-entrepreneurs, which also constitute the conceptual model underlying this study. Techno-entrepreneurs need to develop modes and routines that can cater to the challenges posed by the drivers of frugality in order to develop and commercially utilize the potential of frugal solutions.

Many techno-entrepreneurs from industry nations, however, lack the requisite market knowledge to develop frugal solutions that meet the specific needs of a large group of aspiring customers for *affordable and excellent quality* products (Maira, 2005). As a result, they face problems in developing products for highly price-sensitive markets (Schanz *et al*, 2011). A study of German "Hidden Champions" in China and India by Herstatt et al (2017) found that in more than 70% of the cases the headquarters played a dominant role in the product development and there was little local engagement in terms of product development.

2.2. Frugal vehicles and German component suppliers

Studies of innovation pathways related to frugal passenger and commercial vehicles point to a crucial role played by component suppliers in enabling those vehicles' core value proposition of affordability, fulfillment of specific local needs and meeting of prevalent regulatory norms (Tiwari and Herstatt, 2014; Tiwari and Kalogerakis, 2017). German component suppliers are known to have played an important role in such projects (Palepu *et al*, 2011).

By developing new components for the Tata Nano, the world's most affordable car in terms of price, several German auto-component manufactures enabled a very significant reduction in production costs while ensuring adherence to quality and safety norms. According to Simon (2015: 58), "Bosch developed a radically simplified and much less expensive fuel injection system for use in the Nano". Bosch components alone reportedly account for almost 10% of the Nano's value (Simon, 2015).

Bosch is, however, not the only German automotive supplier contributing to the development of the Nano. Simon (2015: 58) states that nine (un-named) German auto component suppliers "have their parts or their technologies in the Nano". Schuster and Holtbrügge (2011) explicitly name six German firms that have contributed frugal solutions to the automotive industry. These are Bosch, Continental, Freudenberg (Vibracoustic), Mahle (Behr), Schaeffler INA and ZF Friedrichshafen. In addition, Hella, a company specializing in horns and lighting solutions, is also known for having developed frugal solutions (Gautam, 2013; Tiwari and Kalogerakis, 2017). These seven techno-entrepreneurs with documented history of introducing frugal solutions form the sample of investigated firms for a patent and keyword analysis in section 3.

A recent study of the relevance of frugal innovations for the German auto component industry by Bergmann and Tiwari (2017) showed that experts perceive them to be of medium to high importance. The reason advanced is that German auto component manufacturers are globally active and costs reduction has turned into a driving force in this industry. One of the interviewed experts said that "frugal innovation already plays a role in the mind-set of the engineers, who try to eliminate unnecessary functions". Furthermore, this expert pointed out that especially for

the internal, and thus invisible, components in a vehicle, frugal innovation is of very high relevance. Another expert pointed out that the requisite level of frugality often remains unachieved due to the traditional modes and routines in firms, which causes path dependencies and a lock-in situation (Bergmann and Tiwari, 2017: 14-18).

3. Study of frugal innovations by techno-entrepreneurs

3.1. Brief company profiles

The information about the selected techno-entrepreneurs in this section is derived from their respective annual reports for 2016, unless specified otherwise. The information about the patents filed in 2015 is taken from the German Patent and Trade Mark Office (DPMA) online database, while the information about their global position in the auto components business is based on a ranking published by Berylls Strategy Advisors (2017). The companies are listed in alphabetical order.

3.1.1. Continental AG

Continental AG (Continental) is the second largest auto component supplier worldwide. The company is organized in five divisions: Chassis & Safety, Interior, Powertrain, Tires and ContiTech. As of 2016, the company maintains over 400 locations in 56 different countries and employs over 220,000 associates. Sales revenues stood at €40.6 billion, 21% of which came from Asia. R&D takes place at 146 locations worldwide. The company spent €2.8 billion on R&D (ratio to sales revenues: 6.9%) in 2016. The company states as its objective "[…] to bring about sustainable, individual mobility that is highly efficient, causes zero accidents, and is clean, intelligent, and affordable for all" (Continental, 2017). In 2015, Continental was granted 1,128 patents by DPMA.

3.1.2. Freudenberg & Co. KG

Freudenberg & Co. KG (Freudenberg) belongs to the top-100 auto component suppliers globally. The firm is divided in four divisions, i.e. Seals & Vibration Control Technology, Nonwovens & Filtration, Household Products, and Specialties & other business areas. Vibracoustic, one of the auto component suppliers involved in the development of the Tata Nano, is one out of five subsidiary companies belonging to the Seals and Vibration Control Technology business area. Sales revenues of the Freudenberg Group in 2016 stood at €7.9 billion. At year-end 2016, more than 46,000 associates were employed by Freudenberg. The company is active in 57 countries with more than 490 locations. Approx. 3,100 employees of the Freudenberg Group worked on R&D in 2016 while the firm invested €372 million on R&D (ratio to sales: 4.3%). Freudenberg product portfolio for the automotive industry contains among others automotive interiors and anti-vibration components. DPMA reported granting of 84 patents to Freudenberg in 2015.

3.1.3. Hella KGaA Hueck & Co.

Hella KGaA Hueck & Co. (Hella) is a specialized automotive supplier in the field of lightning and electronics, and belongs to the top-50 of the auto component firms globally. In fiscal year (FY) 2015/2016, which runs from June 2015 to May 2016, Hella had about 36,700 employees worldwide and generated sales revenues worth €6.4 billion. Europe accounted for 55% of the revenues, while the Americas contributed another 19%; the rest came from Asia Pacific and other parts of the world. The company is divided into Automotive, Aftermarket and Special

Applications units. Automotive business contributes about 76% of the revenues. Hella is globally active at around 134 locations in over 35 countries. About 6,400 employees are engaged in R&D. Hella invested around €623 million in R&D (ratio to sales: 9.8%) and filed for 172 patents in FY 2015/16. Hella takes a leading role especially in the lightning technology for automotive (Hella, 2016).

3.1.4. Mahle GmbH

Mahle GmbH (Mahle) is a diversified auto parts suppliers, belonging to the top-25 worldwide, and active in segments such as engine systems and filtration. In 2016, Mahle generated annual revenues of €12.3 billion and employed 77,000 associates. The share of Asia Pacific and South American countries in Mahle's business amounted to 24% in 2016, while Europe and North America contributed 50% and 26% respectively. Mahle owns about 170 production locations and 15 major development centres in 33 countries worldwide. The investment for R&D by Mahle in 2016 amounted to €753 million (ratio to sales revenues: 5.6%) and 350 patent registrations were filed in the year. Close to 6,000 employees were working on R&D "at 15 development locations and 12 competence centres" worldwide. Mahle is delivering solutions for the further optimization of the combustion engine as well as in the field of e-mobility (Mahle Group, 2017).

3.1.5. Robert Bosch GmbH

Robert Bosch GmbH (Bosch) is a leading supplier of technology and services in different industries and the world's largest auto parts supplier. The group is divided into four main business units, i.e. Mobility Solutions, Industrial Technology, Consumer Goods, and Energy & Building Technology. It has about 440 subsidiaries and regional companies in close to 60 countries of the world. The group generated revenues worth €73.1 billion in 2016 and employed around 389,000 associates. Asia Pacific is the fastest growing region for Bosch and accounted for 28% of the group revenues in 2016 (Europe: 53%, North America: 17%). The business sector Mobility Solutions accounts for about 60% of the group revenues and is driving the activities for the industry field of auto component supply. The sector is responsible for different fields as electrical drives, starter motors and generators, car multimedia and chassis systems control. Bosch maintains 120 engineering locations globally and invested close to €7 billion on R&D (ratio to sales: 9.5%) in 2016. Close to 59,000 employees work for the R&D division; about half of them outside Germany. In 2015, Bosch was granted 4,198 patents by DPMA.

3.1.6. Schaeffler AG

Schaeffler AG (Schaeffler) is an automotive and industrial supplier that belongs to the top-25 auto parts suppliers worldwide. It produces "high-precision components and systems in engine, transmission, and chassis applications, as well as rolling and plain bearing solutions for a large number of industrial applications". Schaeffler owns several brands like INA, FAG and others. In 2016, Schaeffler generated revenue worth €13.3 billion, over 77% of which came from its automotive business. Contribution of Asian economies to revenues stood at 26%, while Europe's share was 53%. With 17 R&D centres & "additional R&D locations" in 24 countries, 75 production facilities and 86,000 employees spread in around 50 countries, Schaeffler sees itself as "a global player with a local presence". Schaeffler's R&D expenditure in 2016 was around €751 million (ratio to revenue: 5.6%). It had an R&D staff of more than 7,100 employees in 2016, which generated close to 3,000 inventions leading to 2,334 patent applications with DPMA (Schaeffler, 2017).

3.1.7. ZF Friedrichshafen AG

ZF Friedrichshafen AG (ZF) is the third largest German auto component manufacturer and ranks amongst the top-5 worldwide. It had annual sales revenues of €35.2 billion in 2016 and close to 137,000 employees spread across 230 locations in around 40 countries. The organization is set up as a matrix organization with divisions for Car Powertrain Technology, Car Chassis Technology, Commercial Vehicle Technology, Industrial Technology, E-Mobility, ZF Aftermarket and Active & Passive Safety Technology. Around 14,550 employees worked in R&D and the R&D expenditure was almost €2 billion (ratio to sales: 5.5%). ZF sees itself as a "technology and cost leader" in the market. The company reported over 1,720 internal invention disclosures and 1,200 patents in 2016 (ZF, 2017).

3.1.8. Summary of investigated techno-entrepreneurs

Table 1 summarizes key data for the techno-entrepreneurs listed above, sorted according to firm size as measured in revenues generated. The data shows that the firms have a large international presence and are engaged in technological inventions, establishing their fit to the scope of the present study.

No.	Firm	Countries of activity (nos.)	Group revenues in billion euros (2016)	R&D ratio to sales (2016)	Patents granted (2015)[2]
1	**Bosch**	60	73.1	9.5%	4,198
2	**Continental**	56	40.6	6.9%	1,128
3	**ZF**	40	35.2	5.5.%	881
4	**Schaeffler**	50	13.3	5.6%	2,014
5	**Mahle**	33	12.3	5.6%	350
6	**Freudenberg**	57	7.9	4.3%	84
7	**Hella**[4]	35	6.4	9.8%	162

Table 1: Key data of the investigated techno-entrepreneurs[2]

3.2. Patent and keyword analysis

3.2.1. Methodology

We performed a patent and keyword analysis on the 7 investigated techno-entrepreneurs. The patent analysis concerns the timeframe from 2010 to 2015. First, we conducted a patent analysis, looking at the overall patent publication trend since it is considered useful in forecasting emerging technologies (cf. Daim *et al*, 2006). We used the online patent database of the German Patent and Trade Mark Office (DPMA), concentrating only on patent applications filed at DPMA. After identifying the overall trend, we focused on three most important patent classes for the individual firms, as measured by the number of overall patents in these subclasses, within the main class F ("Mechanical engineering; Lighting; Heating; Weapons; Blasting") that is relevant for the automotive industry. We analysed all identified patents within 20 subclasses (total 2,908) for selected keywords relating to frugality as identified by Bergmann and Tiwari (2016). The patent subclass F16K 31/06 ("Operating means; Releasing devices using a magnet") belonged to the top-3 by Continental and Robert Bosch, both. Finally, we identified frugal inventions by filtering out patents that contained at least three

[4] Sorted according to firm size (measured by revenues); data for Hella pertains to FY 2015/2016. Constructed based on the respective annual reports; number of patents taken from the DPMA database.

different frugality keywords. In total 43 frugal inventions were identified. Four of these frugal inventions (patents) will be also showcased in section 4.

3.2.2. General overview

The seven investigated firms were granted total 45,483 national patents by DPMA between 2010 and 2015. Bosch alone accounted for close to 53% of them, followed by Schaeffler (20%) and Continental (12%). The rest of the firms had much smaller shares, i.e. ZF (9%), Hella (2%), Freudenberg (1%) and Mahle (1%). The total number of patents granted to the firms in the sample had increased consistently in this period, even though it sometimes decreased for individual firms. Schaeffler was the only firm in the sample for which the number of granted patents had increased consistently through-out the period of investigation (see Figure 3).

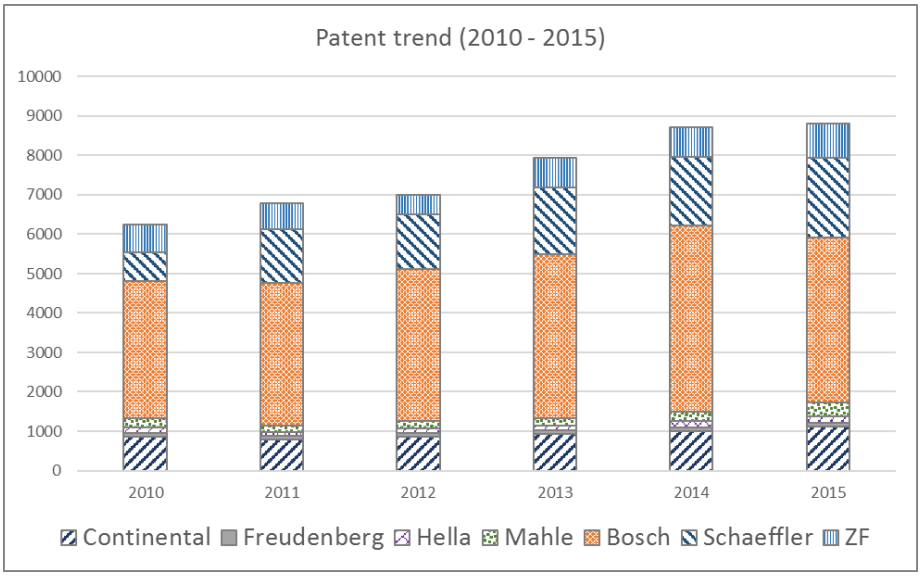

Figure 3: Patent publication trend for the investigated firms (2010-2015)

For a keywords-based content analysis we decided to focus on the three top patent subclasses (8-9 digits level) for the respective firms. These top-3 categories varied from firm to firm depending on their core field of innovation activities within the overall business segment of the engineering patents (main class F), see Table 2. A detailed description of these subclasses can be found in Appendix.

Firm	Most important patent subclasses		
	Top-1	Top-2	Top-3
Bosch	F01N 03/10	F02M 47/02	F16K 31/06
Continental	F02D 41/20	F16K 31/06	F02M 51/06
Freudenberg	F16J 15/32	F16J 15/34	F16F 13/10
Hella	F21S 08/10	F21V 08/00	F21S 08/12
Mahle	F02M 37/22	F02F 03/00	F02F 03/22
Schaeffler	F01L 01/344	F16F 15/14	F16D 13/75
ZF	F16H 03/66	F16H 03/093	F16H 57/04

Table 2: Overview of the most important Patent subclasses for individual firms

3.2.3. Keyword Analysis

The focus on 3 most important patent subclasses for each surveyed firm led to identification of total 2,908 patents. These patents were searched for 7 keywords that were identified from the authors' study of media discourse on frugal innovations in the German-speaking countries (Bergmann and Tiwari, 2016), as reported in section 2.1. Table 3 contains a list of the 7 keywords (the exact search term in German, the intended search strings, English translation of them, and the number of total hits achieved) we used for the analysis.

No.	Search term(s) in German	Intended search string(s) in German	English translation	Total hits
1	robust	robust	robust	256
2	ressource	ressourcenschonend ressourcensparend ressourceneffizient	resource saving resource savvy resource efficient	1
3	funktional	funktional	functional (functionally focused)	363
4	einfacher	einfacher	simpler	849
5	benutzer	benutzerfreundlich	user friendly	0
6	kostengünstig	kostengünstig	cost effective	2140
7	erschwinglich	erschwinglich	affordable	0

Table 3: Overview of surveyed keywords (multiple hits per patent possible)

Cost effectiveness was found to be a key driver of these inventions, followed by simplification efforts, functional focus and robustness. Surprisingly, resource efficiency hardly found *explicit* mention in the investigated patents (see Table 3), even though many patents mentioned other factors leading to resource efficiency.

In a next step, we eliminated the effect of keyword redundancy within individual patents. This elimination ensured that the occurrence of each keyword in a patent was counted only once. The four most important keywords and their relative importance for individual patents are shown in Figure 4.

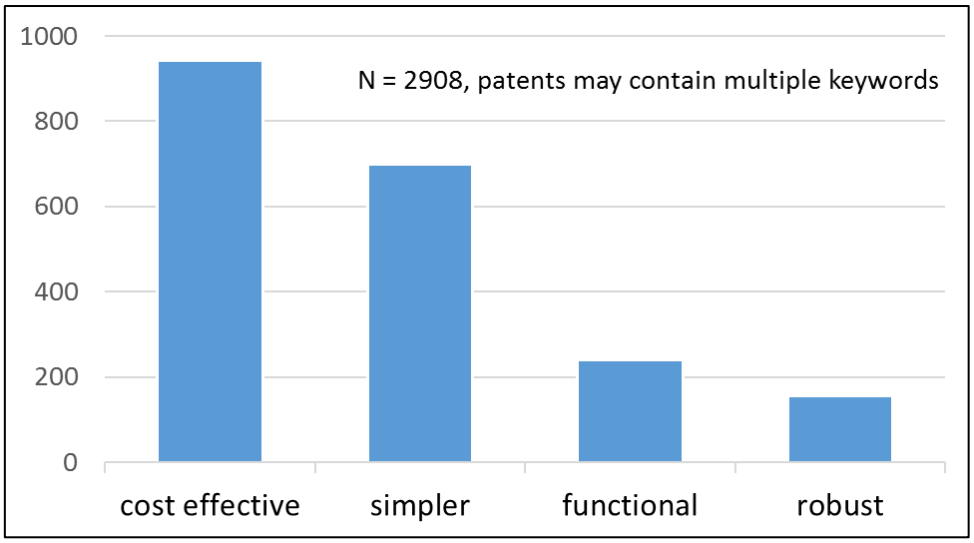

Figure 4: Occurrences of pre-identified keywords in individual patents

With occurrence in 942 unique patents, cost effectiveness continued to constitute a major driving force for the investigated patents, followed by simplification efforts (698), functional focus (239) and robustness (156), see Figure 4. On the other hand, it also meant that as many as 1,966 patents (68%) did not explicitly mention attempts to achieve cost effectiveness. The same logic, obviously, also applies to the other keywords. It must be, however, mentioned that the present study worked only with the aforementioned 7 keywords to generate preliminary insights and did not attempt to capture a more comprehensive picture by incorporating multiple synonyms.

3.3. Frugal Inventions

3.3.1. Identification process

As a next step, we employed results of the keyword analysis to further narrow down the sample for identifying "frugal" inventions. For the purpose of this study, we decided to treat inventions as frugal if the corresponding patent contained simultaneous occurrence of at least 3 of the 4 previously identified keywords. Of the 2,908 identified patents from the 3 top patent subclasses for the seven individual firms, only 1,565 patents actually contained at least one of the four keywords related to frugality. Their number decreased to 375 when the bar was raised to two keyword occurrences and fell significantly further to 43 when the filter criteria was shifted to three keyword occurrences. Only 2 patents, both belonging to Bosch, contained all 4 keywords.

Firm	Sample size (top-3 subclasses)	Frugal Inventions	
		Absolute nos.	Relative share (%)
Bosch	783	14	1.8%
Continental	201	2	1.0%
Freudenberg	76	0	0.0%
Hella	176	0	0.0%
Mahle	120	2	1.7%
Schaeffler	982	12	1.2%
ZF	570	13	2.3%
Total	2908	43	1.5%

Table 4: Prevalence of frugal inventions in investigated firms

As Table 4 shows, the relative share of frugal inventions – measured within the scope of this study – is low (1.5%). The highest share (2.3%) belongs to ZF, followed by Bosch and Schaeffler, while Freudenberg and Hella did not have any corresponding patent in their top-3 patent subclasses. In terms of developments over time it is interesting to note that in 2010 there was only one patent (from Mahle) that fulfilled the frugality criteria (0.3% of the sample size). Since then the share of frugal inventions has increased on a lower absolute level to 1.7% (10 patents) in 2015.

3.3.2. Differences in inventor teams

We contrasted the number of inventors involved in all patented inventions in the sample with the number of those involved in patented frugal inventions. Interestingly, frugal inventions in our sample resulted more often from efforts of a single inventor (51%) than the overall patents (33%). Around 37% of all patents resulted from three or more inventors; sometimes even up to 18 inventors were involved in a single patent. In case of frugal inventions, only 19% of patents had three or more inventors and the maximum number of inventors involved in a frugal invention was seven. Correspondingly, more than 80% of all frugal inventions had resulted from the work of up to two inventors (see Figure 5).

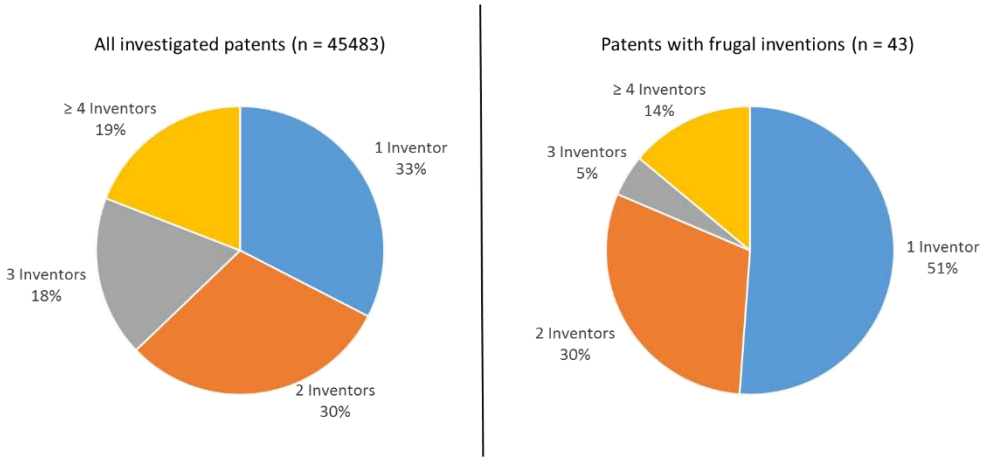

Figure 5: Number of inventors involved in the patented invention

Keeping in mind the small size of the frugal inventions' sample that limits its generalizability, the insights still seem to be plausible in the light of the following reasons:

- Frugal innovations often seek to reduce the complexity of the solution by simplifying construct designs and manufacturing processes. The simplification of individual solutions probably needs less collaborative efforts than the creation of highly complex solutions.
- Frugal innovations still face resistance and acceptance issues and they constitute a minor part of the R&D efforts in the investigated firms. It is possible that the efforts to create frugal solutions are driven mainly by some highly motivated individuals with a frugal mind-set that drives inventors to challenge conventional wisdom. This is also supported by the fact that several individual inventors are found to be involved in multiple patents of frugal inventions.

3.3.3. Extent of global R&D

We analysed the patent data to understand the role of globalization in the creation of frugal inventions in the investigated firms. Generally, a trend towards global innovation could be

observed for all patent activities. While in 2010, 94% of the patenting teams were entirely based in Germany, this share went down to 89% by 2015. In 2015, in 7% cases there was an internationally mixed team of inventors, signalling global innovation. In 4% of cases the entire inventor team was based overseas.

In case of frugal inventions, the share of overseas inventors was much lower (5%), with 3% of entire inventor teams being based overseas and in 2% of cases the teams having a mix of overseas and Germany-based inventors. This can be probably interpreted as an indicator of under-utilization of the potential of global innovation in the investigated firms. Creating frugal solutions generally necessitates a better, deeper and first-hand understanding of, and empathy with, the "problem areas" of the frugal user typically found in the EMDE countries (Basu *et al*, 2013; Tiwari and Herstatt, 2014). In this context, several studies have pointed towards the role of open global innovation networks (OGINs) both within and outside firm boundaries (Tiwari and Herstatt, 2012b; Midler *et al*, 2017), and it appears as if the investigated firms have not yet fully exploited this potential.

4. Selected cases of frugal inventions

4.1. Introduction to patent cases

To further refine our understanding of the frugality implemented in patented technical inventions and to understand the modes employed in its implementation, we present four particularly interesting patents in the following sections. The patent text quoted here has been translated by the authors from German to English. The cases were selected from the sample of 43 patents identified as frugal inventions and represent inventions with both single inventor (cases 1, 2) and multiple inventors (cases 3, 4) as well as with domestic (case 1,2) , mixed (case 3) and entirely foreign-based (case 4) inventor teams.

4.2. Gearbox with simple and cost-effective design

Patent no. DE 102013204452 A1, granted to ZF Friedrichshafen AG, concerns a gearbox, especially a double-clutch transmission for motor vehicles. The patented invention was carried out by a single inventor based in Germany. The patent application was filed on March 14, 2013, and granted on Sept. 18, 2014. According to the claims made in the patent a disadvantage of the state-of-art technology has been "that a high number of shifting elements and wheel planes are required for only a few forward gear stages. In addition, the gearbox requires a lot of space". The application claimed "to provide a transmission which is compact in construction and has few switching elements, […] and has a simple and therefore cost-effective design. Moreover, it is an objective of the present invention to provide a transmission which provides good load switching capability, good hybridization capability, and the possibility of simple expansion." The patent also states that the invention helps to omit a time-consuming and thus cost-intensive setting of respective transmission elements at the corresponding wave, and also cites more instances of reduction in number of components "so that the gear can be designed more cost-effectively" (Wechs, 2013).

4.3. Easy-to-install and reliable holder for a filter device

Patent no. DE 102009009421 A1, granted to Mahle International GmbH, concerns "a particularly easy-to-install but at the same time reliable holding of a filter device" in motor vehicles. The invention was carried out by a single inventor based in Germany. The application

was filed on Feb. 18, 2009 and granted on Aug. 19, 2010. According to the patent claims, traditional filter devices have to be comparatively large to enable a relatively high filter throughput, especially in trucks. To cope with the vibrations while driving, the filter devices must be reliably connected to the body of the truck. Screw connections that are generally used can come loose as a result of the vibrations occurring during the operation of the truck, and also require a considerable mounting or disassembly effort. In addition, there are problems of fatigue when components are used over longer periods of time. The patented invention sets "the filter plug on the bodywork of the motor vehicle by means of a latching connection" which "facilitates assembly and disassembly in a simplified manner compared to previously used screw connections and [… avoids] breaking of the plastic material in the region of the screw connection to the body". "A great advantage of these latching connections", according to patent claim, is that "they can be produced proportionally in a single working step, for example in a plastic injection molding process, together with the filter pot or the filter cover, and can thus be produced extremely cost-effectively". This solution enables a reliable and, at the same time, simple construction of the filter device on the body of the motor while reducing the need for a large component variety, "and is therefore more cost-effective, in particular with regard to storage and logistics costs" (Koball, 2009).

4.4. Electromagnetic switching valve with simple & cost-effective production

Patent no. DE 102009046830 A1, granted to Robert Bosch GmbH, concerns an electromagnetic switching valve (quantity control valve) for measuring fuel amount in vehicles. The invention was carried out by a team of 5 inventors, one of whom was based in Korea, whereas other four were based in Germany. This patent looks into the problem of the then state-of-the-art electromagnetic switching valves used for "controlling the quantity of fuel supplied to a common rail by a high-pressure pump. The working frequency of such valves, in particular in applications in fuel systems of vehicles, can be so high that the mechanical stress on the functional elements as well as the noise development is no longer negligible". The inventor team proposes a solution to this problem by simplifying the electromagnetic switching valve and making the two sections substantially radial-symmetrical. According to the patented claim, this solution "results in a particularly simple and cost-effective production, in particular in simple assembly" that is "easier to construct […] simplifies production and reduces manufacturing costs" (Dogan *et al*, 2009).

4.5. Wear-reducing and resource-saving friction clutches

Patent no. DE 102014211645 A1, granted to Schaeffler Technologies AG & Co. KG, concerns friction clutches that have a wear-compensating spring attached to integral axial extensions of a vehicle body. The invention was carried out by a two-member team based in India. As per claims made in the patent, companies for cost reasons often avoid using self-adjusting friction clutches (SACs) instead opting for rivets, which are fixed on an additional spring and act as a wear-compensating spring. These, however, "have the disadvantage that a large number of individual components must be installed", which ultimately also increases costs. Wear fatigue gets increased too. The patented invention seeks to provide "an alternative to complex, self-adjusting couplings", which is less costly, reduces wear, ensures "a better behavior over the entire service life" while retaining high pedal comfort for the user. The solution avoids "numerous disadvantages with self-adjusting friction clutches" while simplifying the overall assembly process. The patented solution can reduce production lead times and assembly problems. The solution also allows easy maintenance through simple change of the individual

components. Furthermore, the complexity is reduced by using about one-third less parts compared to the existing solutions. This results in several advantages like saving costs, using less space which leads to a better adaptation to the customer needs. According to the patent, the invention eliminates the need for complex geometry of wear-compensating springs. Tool costs can be reduced leading to less material costs. The solution also achieves a lower hysteresis due to the reduction of the contact points. This invention explicitly makes use of standardized wear-compensation springs even with different friction clutches and allows reuse of parts according to the principles of circular economy, reduces waste and fosters environment-friendly solutions. This results in higher flexibility. The wear-compensating spring can be formed from the inner portion of a support spring. It is pointed out that it is possible to also manufacture the wear compensation spring by means of a welding process. Metal strips of rolled and welded material can be combined to prevent larger coils. "The leaf spring-induced load can be reduced because the counterforce of the wear compensating spring against the plate spring is reduced during transport. This can lead to savings on the leaf spring material" (Mani and Rengasamy, 2014).

4.6. Core insights from patent cases

Table 5 summarizes the four cases presented above in terms of modes and routines ("characteristics") employed by the investigated techno-entrepreneurs along certain categories of the firm value chain. It shows that techno-entrepreneurs often resort to simplification of product (component) design with the purpose of reducing the space it requires, the number of parts it needs and the time it needs to get installed. They also resort to standardization of parts to minimize component variety and thus increase economies of scale while also reducing costs of storage and logistics. In production, reduction in assembly time and in the number of steps required for production are sought to be reduced leading to cost effectiveness.

Category	Mode of frugality	Case #1 Gearbox	Case #2 Filter holder	Case #3 switching valve	Case #4 friction clutches
Product Design	Compactness in terms of space needed	✓			
	Simple design/ construction	✓	✓	✓	✓
	Cost-effectiveness of design	✓		✓	✓
	Reduction in number of parts/ components	✓			✓
	Standardization of parts to reduce variety		✓		✓
Performance	Ensuring good (appropriate) quality	✓		✓	
	Ensuring reliability		✓		✓
	Achieving higher flexibility				✓
	Achieving high comfort/ performance			✓	✓
Production	Reducing assembly time	✓	✓	✓	✓
	Reducing number of production steps		✓		
	Ensuring cost-effective production		✓	✓	✓
Distribution	Ensuring cost-effectiveness in storage and logistics		✓		
Customer orientation	Better adaption to customer needs				✓
Sustainability	Reducing need for material				✓
	Ensuring re-use of material				✓
	Minimizing waste				✓

Table 5: Overview of the mode & routines employed in the selected cases of frugal inventions

The cost-effective design, while ensuring an appropriate (good) level of the requisite performance, also may lead to greater flexibility, comfort and/or better performance. At the same time, cost-effective design also may be based on principles of circular economy by reducing the need for material in the first place, but also by intentionally reducing waste and re-using materials.

5. Conclusions & summary

This explorative study set out to generate preliminary insights about the modes and routines employed by techno-entrepreneurs from industry nations when creating frugal solutions. The focus of the study was on technical inventions resulting from R&D efforts, so that a patent and keyword analysis could be performed on selected techno-entrepreneurs from Germany's auto component sector. All techno-entrepreneurs investigated in the study have a documented history of contributing to the development of frugal vehicles.

The study discovered that the number of patented frugal inventions, i.e. patented inventions that simultaneously seek at least 3 of the four pre-defined objectives, i.e. increase cost effectiveness, simplify product, achieve functional focus, and enhance robustness, is relatively low. While 1,565 of 2,908 patents (54%) contained at least one of the four keywords related to frugality, only 375 patents (19%) contained two keywords. In total, only 43 patents (1.5%) contained 3 or more frugality keywords at the same time. Nevertheless, their share amongst all patents in the top-3 subclasses for the investigated firms in a given year has risen from 0.3% in 2010 to 1.7% in 2015.

The results show that cost effectiveness, with occurrence in 942 out of 2,908 (around one-third) unique patents in the investigation sample, is a core driver for inventions in the German auto component sector. Despite the relative importance of cost effectiveness, there are some other highly relevant factors such as the desire/need for simplification. Interestingly enough, simplification, defined by us as elimination of avoidable complexity, also seems to be utilized as a tool to implement cost effectiveness, creating a virtuous, self-reinforcing mechanism. Simplification, therefore, seems to be a key mode to achieve the objective of frugality.

The investigated techno-entrepreneurs' emphasis on frugal innovation seems to be still low. It seems that the development of the frugal inventions in the investigated firms is mainly driven by some highly motivated individuals with a frugal mind-set, which motivates them to challenge conventional wisdom. We could observe engagement of serial frugal inventors in more than one-third of all patented frugal inventions (15 out of 43). One inventor was involved in 8 different frugal patents, another in 5, and 2 more in 3 each. The importance of such personal commitment has also been pointed out by Maira (2015) and Chacko et al (2010), who have documented in the context of India's automobile industry how personal commitments by relevant stakeholders play a key role in holding the costs down. Another reason for the low extent of frugal innovation within the firms could be that organizations, including techno-entrepreneurs, often develop self-reinforcing mechanisms which lead to a disadvantageous lock-in situation increasing the risk of becoming inflexible. By losing the ability to "adapt to new circumstances or to better alternatives" they may get "confined to the existing path that replicates inefficient solutions" (Schreyögg and Sydow, 2011: 325).

The analysis has shown that a principle mode of achieving frugality lies in the simplification of product design, which often leads to compact products with better cost structures, higher reliability and *requisite* quality. Furthermore, production processes have to be optimized to reduce the number of production steps and better utilize assembly time. Responsible use of materials is achieved by reducing the need for material and ensuring its better re-use as well as by minimizing waste. Apart from ensuring better monetary affordability, the responsible use of materials leads to greater societal and environmental affordability of products and services and

leads to affordable green excellence. Finally, frugality has to be implemented in the entire value chain, including in distribution. Figure 5 summarises the key results of this analysis.

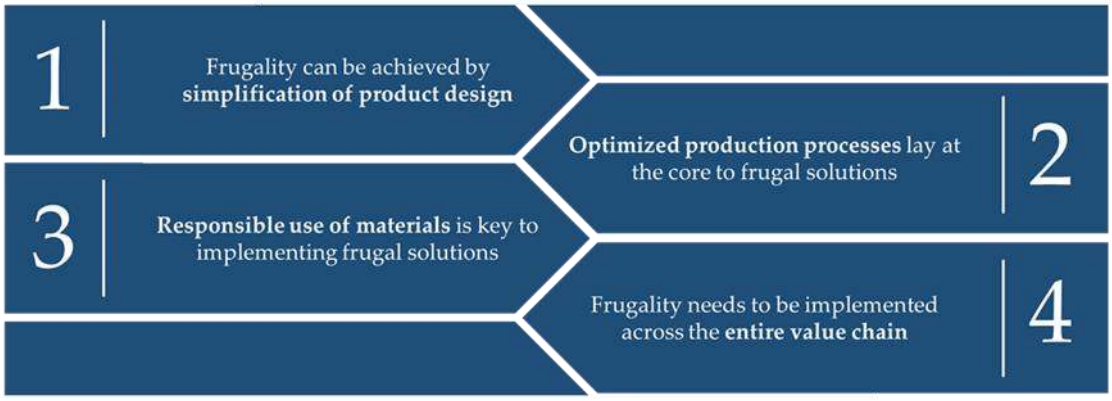

Figure 6: Key results of the study

To add a note of caution, this explorative study focussed only on a small sample of techno-entrepreneurs in a specific industry and obviously also faces certain limitations. First of all, we have based our study on the known keywords for frugality so that some other eventual dimensions may have remained unexplored. Furthermore, we have not exhausted synonyms for the chosen keywords so that incorporating other variants may lead to identification of some more frugal inventions. The sample of techno-entrepreneurs investigated in this study is small and has a regional and industry focus, so that the generalizability of results may have been also affected. The patent analysis is presently based on 20 patent subclasses and should be ideally expanded in a future research project.

Nevertheless, despite the limitations mentioned above, there is also reason to believe that the preliminary insights generated by the present study possess the requisite robustness. The identified modes and routines of frugality are commensurate with the results of a study of frugal innovation pathways in India done with a differing research design by Tiwari and Kalogerakis (2017). They also validate to some extent the findings about the media perception of frugal innovation in German-speaking countries by Bergmann and Tiwari (2016). A notable exception is the emphasis on resource efficiency which was not explicitly confirmed by the present study. The resource efficiency is, however, implicitly a key factor as the case studies of individual frugal inventions in section 4 has demonstrated. On the whole, there may be a great overlap in the modes and routines of frugality across country contexts, even if the level of acceptance for frugality may vary. For future research it may be very useful to conduct cross-country and cross-industry comparative studies and investigate the potential similarities and differences to further validate the results and to generate more nuanced insights and to further enhance their usefulness for the relevant stakeholders in business, research and policy arenas.

Summarizing, in this study we have identified the modes and routines that are particularly helpful in technological realization of frugal innovations. Cost effectiveness, greater customer orientation and environmental sustainability can be often achieved by ensuring simplicity, and in case of existing products through simplification, of design and production process, as well as by standardization of components as they reduce avoidable complexity. This shows that when creating a frugal solution, the focus should not lie merely on product development. Rather, frugality can only be achieved by a holistic approach that encompasses the whole value chain, including logistics and waste management. The results are potentially beneficial for techno-entrepreneurs across industry sectors and product domains.

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Appendix: Patent subclasses according to DPMA

Serial no.	Patent subclasses	Description
1	F01L 01/344	Valve-gear or valve arrangements changing the angular relationship between crankshaft and camshaft, e.g. using helicoidal gear
2	F01N 03/10	Exhaust or silencing apparatus having means for purifying, rendering innocuous, or otherwise treating exhaust by thermal or catalytic conversion of noxious components of exhaust
3	F02D 41/20	Output circuits, e.g. for controlling currents in command coils (current control in inductive loads in general H03K 17/64)
4	F02F 03/00	Pistons
5	F02F 03/22	Pistons the fluid being liquid
6	F02M 37/22	Arrangements for purifying liquid fuel specially adapted for, or arranged on, internal-combustion engines, e.g. arrangement in the feeding system
7	F02M 47/02	Fuel-injection apparatus operated cyclically with fuel-injection valves actuated by fluid pressure of accumulator-injector type, i.e. having fuel pressure of accumulator tending to open, and fuel pressure in other chamber tending to close, injection valves, and having means for periodically releasing that closing pressure
8	F02M 51/06	Fuel-injection apparatus characterised by being operated electrically: Injectors peculiar thereto.
9	F16D 13/75	Features relating to adjustment, e.g. slack adjusters
10	F16F 13/10	Units comprising springs of the non-fluid type as well as vibration-dampers, shock-absorbers, or fluid springs, the wall being at least in part formed by a flexible membrane or the like (F16F 13/12-F16F 13/18 take precedence)
11	F16F 15/14	Suppression of vibrations in systems using freely-swinging masses rotating with the system
12	F16H 03/093	Toothed gearings for conveying rotary motion with variable gear ratio or for reversing rotary motion with two or more countershafts
13	F16H 03/66	Toothed gearings for conveying rotary motion with variable gear ratio or for reversing rotary motion composed of a number of gear trains without drive passing from one train to another
14	F16H 57/04	Features relating to lubrication or cooling (control of lubrication or cooling in hydrostatic gearing F16H 61/4165)
15	F16J 15/32	Sealings with elastic sealings, e.g. O-rings
16	F16J 15/34	Sealings with slip-ring pressed against a more or less radial face on one member
17	F16K 31/06	Operating means; Releasing devices using a magnet
18	F21S 08/10	Lighting devices intended for fixed installation specially adapted for vehicles
19	F21S 08/12	Lighting devices intended for fixed installation providing a single shaped beam, e.g. asymmetric beam, e.g. for penetrating fog or for preventing glare
20	F21V 08/00	Use of light guides, e.g. fibre optic devices, in lighting devices or systems