Conditions of implementation for frugality in engineering and innovation processes

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Abstract

How most countries around the world do business has a significant impact on the environment. For too long, the negative external effects of production and consumption have been neglected. A rethinking towards the reconciliation of economy and ecology is necessary in order to ensure environment-friendly protection of prosperity. However, in comparison, green products are often expensive, and inexpensive products are often associated with higher environmental damage. The early inclusion of low-income households is an opportunity to replace consumption of environmentally harmful products faster and to accelerate the change to a greener economy. Frugality in product development and innovation processes is able to combine green product characteristics with low costs.

In this dissertation, the implementation conditions of the emergence of advanced frugal product characteristics in innovation processes are investigated, which are then called Advanced Frugal Innovation. While a stronger focus is put on the product development process in the scientific literature, also systemic and social conditions are brought to the fore in this dissertation. Both technological capabilities and conducive systemic and societal conditions are essential prerequisites for the emergence of Advanced Frugal Innovation. The empirical findings indicate that societal framework conditions do not currently facilitate the development of Advanced Frugal Innovation in Germany.

Due to a lack of usable prior research, the findings of this dissertation are based on an exploratory research approach. In addition to using relevant academic literature and deducing from existing theories and concepts, qualitative and quantitative data are examined. For this purpose, the focus is on a survey of companies in the manufacturing sector in Hesse and Lower Saxony. The results of this dissertation offer first empirical findings, insights into the development of Advanced Frugal Innovation and provide an impulse for further research.

Keywords: *Sustainability, Advanced Frugal Innovation, Frugal Design Principles, Innovation Systems, Multi-Level Perspective, Green Technologies, Affordable Products, Competitiveness, Transition*

Zusammenfassung

Die Art des Wirtschaftens, wie sie in den meisten Ländern dieser Erde betrieben wird, geht mit ernsten Umweltauswirkungen einher. Zu lange wurden negative externe Effekte der Produktion und des Konsums vernachlässigt. Ein Umdenken hin zur Vereinbarung von Ökonomie und Ökologie ist notwendig, um die Umweltverträglichkeit des Wohlstandes zu gewährleisten. Allerdings sind Grüne Produkte oft teuer und günstige Produkte häufig mit höherer Umweltschädlichkeit verbunden. Die frühzeitige Beteiligung von Haushalten mit geringen Einkommen am grünen Konsum, stellt eine Möglichkeit dar, den bestehenden Konsum umweltschädlicher Produkte schnell zu ersetzen und beschleunigt den Wandel zu einer ökologischeren Wirtschaft. Frugalität in der Produktentwicklung vereinigt grüne Produkteigenschaften und niedrige Preise.

In dieser Dissertation werden die Umsetzungsbedingungen der Herausbildung fortschrittlich frugaler Produkteigenschaften in Innovationsprozessen untersucht, die als Advanced Frugal Innovation bezeichnet werden. Während in der Literatur ein stärkerer Fokus auf den Produktentwicklungsprozess gelegt wird, werden in dieser Dissertation auch systemische und gesellschaftliche Rahmenbedingungen berücksichtigt. Sowohl technologische Fähigkeiten als auch ein förderliches Unternehmensumfeld sind wesentliche Voraussetzung für die Entstehung von Advanced Frugal Innovation. Die aufgeführten empirischen Befunde deuten darauf hin, dass die bestehenden gesellschaftlichen Rahmenbedingungen in Deutschland die Entwicklung von Advanced Frugal Innovation nicht begünstigen.

Aufgrund des Mangels verwertbarer Vorarbeiten stützen sich die Erkenntnisse dieser Dissertation auf einen explorativen Forschungsansatz. Neben der Verwendung einschlägiger wissenschaftlicher Literatur und Deduktion bestehender Theorien und Konzepte werden qualitative und quantitative Daten untersucht. Im Vordergrund steht dazu eine Befragung von Unternehmen des Verarbeitenden Gewerbes in Hessen und Niedersachsen. Die Ergebnisse dieser Dissertation bieten erste empirische Befunde, Einblicke in die Zusammenhänge zur Entwicklung von Advanced Frugal Innovation und stellen einen Impuls für weitere Forschung dar.

Schlagworte: *Nachhaltigkeit, Advanced Frugal Innovation, Frugale Design Prinzipien, Innovationssysteme, Multi-Level Perspective, Grüne Technologien, Erschwingliche Produkte, Wettbewerbsfähigkeit, Transition*

Acknowledgment

„Wirtschaft ist der effiziente Umgang mit knappen Ressourcen“

(Ludwig von Mises)

Seit Beginn meines Studiums begleitet mich das obenstehende Zitat von Ludwig von Mises. Es fasst die Fähigkeiten unseres Wirtschaftssystems im Kern zusammen und zeigt, welche Rolle es für die Lösung der aktuellen globalen Herausforderungen spielen kann. Beim Lesen des Antrags des Forschungsprojekts in dessen Rahmen diese Dissertation verfasst wurde, wurde ich an dieses Zitat zurückerinnert. Advanced Frugal Innovation stellen in diesem Zusammenhang eine Rückbesinnung auf diesen Hebel dar. In der Vergangenheit haben wir es als Gesellschaft verlernt, diesen Hebel zu nutzen. Negative externe Effekte auf die Umwelt wurden ignoriert und Knappheiten im Ausstoß von Emissionen und der Förderung von Ressourcen zu spät in das zentrale gesellschaftliche Bewusstsein gerückt. Ich bin dankbar, in den vergangenen drei Jahren in diesem Bereich geforscht haben zu dürfen und somit einen Beitrag zur Entwicklung einer umweltfreundlicheren Wirtschaftsweise geleistet zu haben.

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Abbreviations

AFI	Advanced Frugal Innovation
ASB	Aggregated Societal Benefit
BOP	Bottom of the Pyramid
FDP	Frugal Design Principle
EB	Environmental Benefit
ETS	Emissions Trading System
FI	Frugal Innovation
FoF	Factor of Frugality
IISc	Indian Institute of Science
IIT	Indian Institute of Technology
ILO	International Labor Organization
MIS	Mission-Oriented Innovation System
MLP	Multi-Level Perspective
MNC	Multinational Corporation
NIS	National Innovation System
OECD	Organization for Economic Co-operation and Development
RIS	Regional Innovation System
SEB	Socio-Economic Benefit
TIS	Technological Innovation System
UFI	Unrefined Frugal Innovation
S&T	Science and Technology

CHAPTER ONE

Introduction

1.1 Motivation

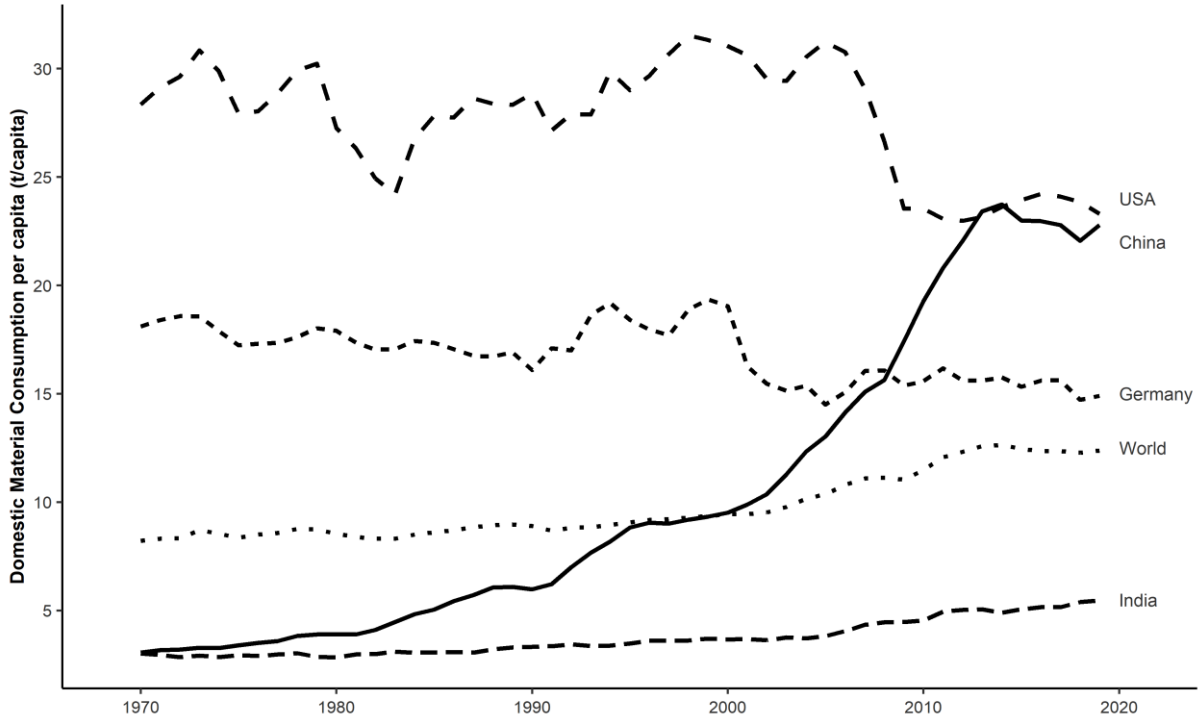
Two developments can be identified as major challenges of this century: A persistent high pressure on the environment due to increasing emissions of climate-damaging gases and material consumption (Liu et al., 2022; United Nations Environment Programme, 2022), and a continuously growing world population. Simultaneously, it has been possible to further reduce the proportion of people affected by poverty and hunger in recent decades (Deutsche Welthungerhilfe, 2022; United Nations, 2022). Especially in the emerging economies, more people have been able to participate in prosperity and increase their standard of living. Both challenges are interrelated and it is necessary to feed more people, let them participate in the prosperity and to minimize the resulting environmental impact to stay within the planetary ecological boundaries (see Rockström et al., 2009; Steffen et al., 2015). Although material consumption decreases in industrialized countries like Germany and the USA, it continues to increase globally, including the most populous countries India and China (Figure 1).

Recent studies explicitly show the problem of high material demand using the example of energy transition. According to their findings, a global supply with renewable energies is impossible given the current technological status and the existing resource stock, since critical raw materials such as cobalt and lithium are not available sufficiently (e.g. Kavlak et al., 2015; Moreau et al., 2019). In addition to more advanced technologies, it is crucial to incorporate product design approaches and technologies that use fewer materials per product with the same or higher quality and usability.

This dynamic requires products that are environmentally friendly but affordable and qualitatively competitive. Products that improve efficiency on these dimensions are called Advanced Frugal Innovation (AFI) (Barnikol & Liefner, 2022; Liefner et al., 2020; Rao, 2017a). Combining these product characteristics enables to supply broader population groups with green products, whereby in particular the inclusion of lower income groups and increased competitiveness of these products in highly competitive

markets is to be emphasized (Gupta, 2012; Rao, 2013; Zeschky et al., 2011). By this, the appeal of green products is further enhanced, price-sensitive customers can consume green products, and the transition to a greener economy can be accelerated. Achieving this objective may be challenging, despite its seemingly simple nature. It requires to change learned principles in the development of products; what is necessary must be prioritized over what is possible in the future. This change must be accompanied by changing institutions, adapt infrastructure and increasing access to necessary knowledge.

Figure 1: Development of material consumption per capita worldwide



Data: United Nations Environment Programme, 2023

The prerequisites for the emergence of AFI range from targeted product development to overall social conditions. Research on frugal innovations focuses mainly on the framework conditions in which low-cost products are created (e.g. Annala et al., 2018; Lim et al., 2013; Zeschky et al., 2014b), but the possibilities of technological progress and new materials are often neglected (see Rao, 2021, 2020, 2018, 2017c, 2017b, 2017a). Transition research mainly focuses on the development towards a general target like sustainability (e.g. Calvert et al., 2017; Coenen et al., 2012; Hansen and Coenen, 2015). Largely ignored is the combination of previously contradictory targets and their structural societal background like green and low-cost product

characteristics. Integrating of these product characteristics as an innovation goal is a superordinate task whose successful implementation must take place on a broad societal front.

This dissertation aims to contribute to understanding the societal and systemic influences on the development of environmentally friendly and affordable products. Forming the capability to combine these product specifications in companies, regions and nations is essential to enable sustainable growth and prosperity for a broad world population in the face of current challenges.

1.2 Theory and research subject

This dissertation positions itself in the interdisciplinary research field of frugal innovation. The existing perspectives from engineering (e.g. Rao, 2022, 2021, 2020, 2017c, 2017b, 2017a, 2014), innovation management (e.g. Agarwal et al., 2021; Altmann and Engberg, 2016; Brem et al., 2020; Tiwari and Bergmann, 2018; Weyrauch et al., 2020), development research (e.g. Leliveld and Knorringa, 2018; Peša, 2018) and international business (e.g. Isaac et al., 2018; Santos et al., 2020; Sinkovics et al., 2014; Winterhalter et al., 2020, 2017; Zeschky et al., 2014a), are extended by an economic geographical perspective. Filling this gap, this dissertation offers a contribution to theory, methodology and empirics for frugal innovations of the advanced type.

1.2.1 Advanced Frugal Innovation

For more than a decade, research has been carried out for a type of new products that convince with a simpler and more goal-oriented design and are significantly cheaper than existing products: Frugal Innovations (FI). A widely accepted definition by Weyrauch and Herstatt (2016) define three characteristics as crucial: concentration on core functionalities, optimized level of performance and substantial cost reduction. Following on from this basic definition, different forms of frugal innovation can be identified in the literature, which can be linked to this definition in varying degrees. Many authors also attribute sustainability to this form of innovation (e.g. Albert, 2019), but the environmental impact of many products labeled as FI is harmful (Hossain, 2021a). There is no final definition for this form of innovation (see Brem, 2017; Hossain, 2021; Stöber et al., 2023) since the research field still has to structure itself. This definitional disagreement makes the research field confusing and makes scientific

progress more difficult. This dissertation focuses on a special form of FI, the Advanced Frugal Innovation.

As can also be observed in the general literature on FI, a final definition for AFI cannot be regarded as given, although it is clearer in terms of applicability, technological requirements and possible customer groups. The main definitional rationale derives from engineering and is related to the methodological framework of action *Factor of Frugality (FoF)* and was first mentioned by Rao (2017c). Rao used the idea of AFI to add an advanced component to FI that enhances the potential of this form of innovation, strengthens the benefits to society, and provides an impulse for further research needs. The understanding of the conceptualization of AFI changed throughout the Articles included in this dissertation, especially between the first (see Chapter 2) and second Article (see Chapter 3). This may be due to the operationalization approach elaborated for empirical investigation in the second Article. A final definition would be too early for this state of AFI research, however, the understanding of AFI applied in this research allows socio-economic and environmental characteristics to be taken into account. The empirical findings of this dissertation show that product development and design are not the only factors that determine final product characteristics and the innovativeness of a product, but that social and systemic factors also influence them.

The understanding of AFI that should be applied to interpret the results of this dissertation consists of three dimensions: Environmental (1), socio-economic (2) and aggregated societal benefit (3). According to type and form of a product, the environmental benefit (1) can be determined by the environmental impact of product components, product design, production, usage, and recycling at the end of product life. The variables to be considered may vary between product categories and include, for example, the type of energy used, materials, and recyclability. The socio-economic benefit (2) primarily covers the cost or price side of a product, taking into account, product development, production, usage and recycling of the product components. This dimension signals participation in consumption for broader population segments. The benefit of these two dimensions can be measured in comparison to competitors. Accordingly, a lower purchase price and the using of more environmentally friendly energy are positive benefits in both dimensions. The third dimension, aggregated societal benefit (3), represents the balance of the environmental and socio-economic

dimensions. This is crucial because the positive balance between environmental and socio-economic benefits indicates the innovativeness of a product. Accordingly, understanding of Advanced Frugal Innovation in the sense of this dissertation means to include all products that create a new efficiency between environmental and socio-economic benefits exceeding the market average. A more detailed explanation of this definition can be found in Chapter 3. In this dissertation, AFI is measured from a societal perspective and investigates how technologies are used in societies.

In a Schumpeterian (1934) sense, AFI can be understood as a new or more efficient combination of environmental and socio-economic beneficial product characteristics, enabled, among others, by new frugality-related design. In this context, AFI can also be seen as Green and Competitive Innovation (Porter & Van Der Linde, 1995b, 1995a), not only serving the upper end of the market, but also directly touching the middle and lower end of the market. By this combination AFI have a disruptive character (Christensen, 1997) if they convince by quality in market.

1.2.2 State of research

Since the research field of FI is comparatively young, there are no recognizable dominant currents, disciplines or competing theoretical approaches at the present time. As described in the previous Chapter, the forming of a standardized definition is an ongoing challenge of the research field (e.g. Hossain, 2021; Stöber et al., 2023), which impedes the formulation of generally valid statements. The emergence of different subcategories, such as AFI, shows that there is still a long way to go. At the same time, the subcategories promote the necessity of a differentiated perspective on FI and may enable the development of a possible comprehensive definition in the first place.

Due to the diversity of products that are considered under the terminology Frugal Innovation, a uniform theory is not given. Researchers differ according to degree of technological sophistication, geographical and cultural context, consumer groups, and motivation to innovate (e.g. competitiveness vs. improvement of quality of life). It is common that, like other innovations, FI is often preceded by a pressure situation involving resource constraints affecting consumers or producers, and attempts to enable consumption against these constraints through frugal design principles. Theoretical fragments exist for the research field of FI and may also be valid for AFI. Based on the current state of research on FI, four theoretical dimensions can be

identified that are relevant for AFIs: Market and societal demand, Frugal Mindset, Frugal Design Principles and systemic and technological capabilities.

1.2.2.1 Market and societal demand

As with other forms of innovation, demand and social pressure can be cited as the major reason for implementing frugality in innovation processes. The main driver, especially for Western companies, is price competition with companies from emerging markets such as China and India, which have low production costs and increasingly trained personnel. Frugal innovations offer the opportunity to maintain or regain competitiveness and to counter the pressure of low-cost competitors (Zeschky et al., 2011). The shift in the cost-performance ratio towards better performance at lower cost offers a disruptive potential that goes beyond emerging markets (Lim & Fujimoto, 2019; Rao, 2013). In addition, it is becoming increasingly apparent that the pricing strategy of many Western companies poses a risk by mainly targeting the most affluent customers especially in Western economies (Prahalad, 2012). The population of the emerging markets, who have been able to raise their standard of living in recent decades (Levänen et al., 2022) make an enormous market volume and growth potential among other things through the inclusion of the Bottom of the Pyramid (BoP) (Lim et al., 2013).

The dominant pressure in Western markets is to develop more environmentally friendly products and technologies (De Marchi, Molina-Morales, et al., 2022). This pressure is driven socially by customer demands and legally binding requirements such as Eco-design Directives or the European Emissions Trading System (ETS). Companies move between these two poles of pressure, with one predominating depending on the market. Meeting both interests simultaneously requires a high level of capabilities and motivation, which is why companies tempt to give in to only one side (Levänen et al., 2022). Particularly in the emerging and developing economies, the fight against poverty is an additional issue from a societal perspective. The lack of access to infrastructure and financial resources requires new design approaches that make do with less and, above all, use what is available (George et al., 2012; Prabhu, 2017). Examples such as the low-cost portable ultrasound scanner and electrocardiogram (Yasser Ahmad Bhatti, 2012) or affordable eye test via smartphone (Yasser A. Bhatti et al., 2017) illustrate how modern technologies can be used to integrate people in rural areas with limited financial resources and infrastructure into the health care system.

1.2.2.2 Frugal Mindset

Result of this pressure mentioned can be a mindset that favors the development of FIs and AFIs. It is described as the capability of inventors to do more with less in a resource-constrained environment (Yasser Ahmad Bhatti & Ventresca, 2013; Iqbal et al., 2021; Soni & Krishnan, 2014; Winterhalter et al., 2017). Geographically, this trait is attributed to emerging markets, in particular India, because the frugal mindset enforces creative problem solving through mainly cultural and institutional structures (Ananthram & Chan, 2019; Soni & Krishnan, 2014). Forming this mindset is encouraged by a high tolerance of uncertainty, which, for instance, is lower in Germany than in India (Soni & Krishnan, 2014; Swierczek & Hirsch, 1994). The high tolerance of uncertainty creates a culture of failure that favors trial and error processes in product development, which is attributed to the frugal mindset (Krohn & Herstatt, 2018; Levänen et al., 2016). However, this form of mindset is not only acquired through socialization, but can also be learned by inventors, managers and companies (Krohn & Herstatt, 2018; Zeschky et al., 2011). The frugal mindset therefore involves developing of strategies and focusing on the essentials that facilitate greener and more cost-effective products with the help of frugal design principles.

1.2.2.3 Frugal Design Principles

Frugal Design Principles (FDP) encompass the entire life cycle of a product from conception through production and application to the use of product components after their end of life (Liefner et al., 2020). The techniques of FDP differ in sophistication and required technological capabilities and are often discussed in context of physical products. However, examples such as Ikea (Tiwari et al., 2017), M-Pesa (Altamirano & Beers, 2018), Space-X (Rao, 2017b), or Airbnb (Prabhu, 2017; Tiwari et al., 2017) illustrate multiple ways of application. A crucial factor for almost all techniques of frugal design principles is to consider the use of a product and offers consumers what they need, thus avoiding a Simpson paradox (Simpson, 1951) and wasting resources (Rao, 2017b). Classical techniques originating from general research are concentration on core functions and the optimization of the performance level (Weyrauch et al., 2020; Weyrauch & Herstatt, 2016). There are also more concrete approaches that provide a framework for the development of frugal products, but they often require trained developers (Brem et al., 2020; Rao, 2017b). Constrained-Based Thinking (Agarwal et al., 2017, 2021), for example, is a creativity approach to product development that can be applied to the development of FIs. The most concrete approach is the Factor of

Frugality (FoF) (Rao, 2017c, 2018, 2019) from the field of frugal engineering (Rao, 2022) which can be applied to physical products. FDPs are closely related to the general technological progress. The unfolding of potential is moderated by the range of available technologies and materials that should be recyclable, green, lightweight, robust and affordable. Examples are sophisticated materials like biogenic carbon (Arnold, Brück, et al., 2018; Arnold, De Palmenaer, et al., 2018), aero graphite (Mecklenburg et al., 2012) or natural materials like bamboo (Devi & Kumar, 2018). In general, the list of frugal design principles is not yet complete and will be further filled by identifying existing and developing new techniques, materials, strategies and others. For the purpose of this dissertation, FDPs include techniques that modify the form of a product in a way that minimizes its environmental impact and product cost while maintaining functionality and quality.

1.2.2.4 Systemic and technological capabilities

The starting shift of frugal innovation research from simple goods to technologically more sophisticated products and technologies implies a greater consideration of technological and systemic capabilities to build innovation. The strong focus of FI research on products for the least affluent part of the world's population often implies the use of less technology to address a lack of infrastructure, such as access to energy, or the use of tinkering and trial and error to compensate missing knowledge and technologies (e.g. Brem et al., 2020; Leliveld and Knorringa, 2018). However, the mentioned examples (see Chapter 1.2.2.3) show that the technological demand for FI, at least of the advanced type, can be much higher, going beyond simple trial and error and requiring specialized knowledge. Although there are isolated paper that point out and emphasize that, for example, external knowledge is required for the development of FI (see AlMulhim, 2021), the systemic and societal perspective on the implementation of frugal technologies and products has so far remained largely unfounded.

1.3 Data and Methodology

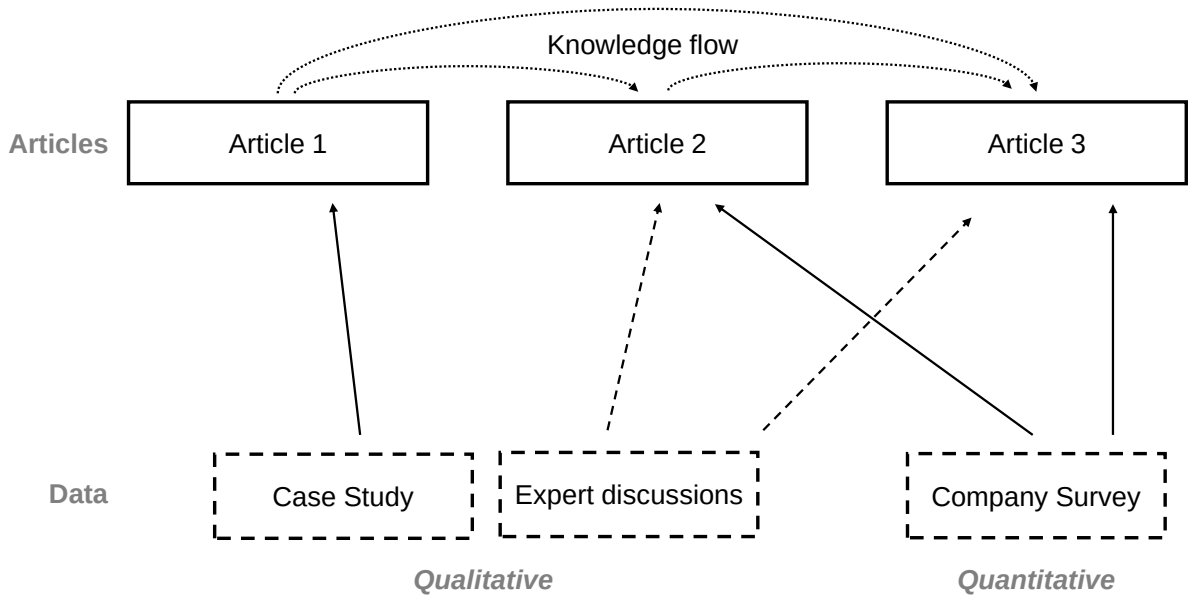
To answer the central research question, qualitative and quantitative methods are used in the individual Articles and Chapters of this dissertation (see Figure 2). Due to the conceptual character of Article 1, the data basis used in the case study is qualitative. The data basis of Articles 2 and 3, on the other hand, is predominantly quantitative,

statistical descriptive analysis. In addition, expert discussions were held to classify the quantitative data.

In addition to a literature review a case study was conducted in Article 1, to show the connection between FI and existing theory concepts. The data on which this is based are extensive interviews with the company Fagus-GreCon Greten GmbH & Co. KG as well as product data sheets and publicly available information of the company. The company was chosen as a case study because it stands out in the market for its particularly frugal product design and is engaged in both emerging markets and industrialized countries.

Along the use of quantitative data, qualitative data in the form of expert discussions have also been incorporated into Articles 2 and 3. The measurement construct developed in Article 2 was discussed with relevant experts on FI during a workshop on AFI and in its consequence slightly modified. The initial findings used for Articles 2 and 3 were also discussed with policy makers, consultants, entrepreneurs, and engineers in two expert discussions. The results of these discussions have been incorporated into Articles 2 and 3, improving the interpretation of the results, and offering approaches for policy implications.

Figure 2: Datatype used for the Articles



The quantitative data was collected mainly with the support of the Unternehmerverbände Niedersachsen e.V. and HA Hessen Agentur GmbH. Currently,

there is no public data set which categorizes products as AFI. Accordingly, the data used had to be collected. The two mentioned partners in Hesse and Lower Saxony enabled the data gathering. The questionnaire was designed to cover a wide range of variables but at the same time focus on querying the essential information (Appendix A). Since there is still limited prior research on this topic, the main indicators that being considered on the basis of the conceptual findings from Article 1 (see Chapter 2) were queried. The call for questionnaires was distributed between May and July 2022 for four weeks in each of the two German federal states. Due to the aftermath of the Covid-19 pandemic and a challenging situation for companies due to the beginning war in Ukraine, participation motivation was low. This is evident in the response rate and usability of the results. Nevertheless, the data set provides significant and meaningful data that offers a first-time look at AFI because it does not exist in current literature on FI in general in this form and significance. These data provide the basis for Articles 2 and 3.

The methods used to evaluate the quantitative data are mainly simple and general statistical and descriptive analyses. This mainly is due to the low number of cases, which does not allow a valid and reliable application of more elaborated analyses. Nevertheless, the carefully selected analysis methods generate valid and significant results. It should be noted that the correlation analyses in Article 2 are performed according to Spearmen (1904) and in Article 3 according to Pearson (1900) although the data basis is very similar. This is due to the aggregation in Article 3, which slightly modifies the scale level. These very similar calculations with a slightly different orientation correspond to the individual data characteristics in a better manner. In addition, this dissertation developed new ways of presenting the data that allow to evaluate companies, industries, markets and social structures in the context of AFIs and beyond. More detailed results on the distribution of the variables used in the quantitative analyses can be found in Appendix B and Appendix C.

1.4 Thesis structure and research context

This dissertation is the result of the research project "Implementation conditions for frugality in innovation processes" of the Institute of Economic and Cultural Geography of Leibniz University Hannover in cooperation with the Indian Institute of Technology Madras in Chennai, India. The research project was funded by the Lower Saxony Ministry of Science and Culture as part of the *PRO*Niedersachsen* initiative (grant

number: 76ZN1894 (VWVN 1466)). The original research strategy included interviews with and surveys of companies in India and Germany. The Covid-19 pandemic and related travel restrictions to and from India have necessitated an adjustment of the research strategy so that the Indian perspective was included less than planned. Consequently, the scope of analysis essentially comprises the manufacturing sector in Germany. The central research question of this dissertation is called: "Which framework conditions are necessary for frugality to prevail in innovation processes?"

1.4.1 Dissertation Articles

As described in Chapter 1.2.2 the current state of research, especially from an economic geographical perspective, shows a research gap that encompasses theory, methodology and empiricism, thus the overall research strategy entails an explorative approach. The individual Articles comprise sub-questions that serve to answer the general research question and are listed and explained individually in the individual Articles.

Table 1: Overview of dissertation Articles

Title and author(s)	Objective	Data and Methods	Publication status
The prospects of advanced frugal innovation in different economies *Julian Barnikol, Ingo Liefner*	Conception of theoretical framework for the development of AFIs from an economic geographical perspective.	Case study of a spark extinguishing device by interview and product data sheets	*Technology in Society (Published)* DOI: 10.1016/j.techsoc.2022.102081
Serving society at large. Operationalization and Evidence of (Advanced) Frugal Innovation in Industrialized Economies. *Julian Barnikol, Ingo Liefner*	Operationalization and development of a flexible measurement concept for AFI and FI. Demonstration of the existence of AFI in an industrialized country and detection of possible development paths for advanced frugal products.	Statistical analysis based on primary collected product data of a company survey	*Technological Forecasting and Social Change (Under Review)*
Green and Competitive: Who influences the development of	Analysis of the societal and innovation system-related framework conditions for the	Statistical analysis based on primary	*Technology Analysis & Strategic*

advanced frugal product characteristics? *Julian Barnikol*	development of AFIs. Deduction of implications for individual societal actors.	collected product data of a company survey	*Management (Submitted)*

In Article 1 (Chapter 2), the characteristics of AFI are conceptually linked to existing theoretical approaches from economic geography and illustrated by a case study. From a theoretical perspective, the concepts of innovation systems and multi-level perspective are essentially considered. Ingo Liefner contributed to this Article in the context of conceptualization as well as writing smaller parts. Article 2 (Chapter 3) covers the development of a new methodological approach to measure AFI that provides also an alternative to the existing and immature measurements of FI. As part of the operationalization process, definitional considerations are discussed. In addition, Article 2 proves the existence of AFI in the German manufacturing sector and detects possible development paths of AFI from a market perspective. The contribution of Ingo Liefner mainly refers to the writing of smaller sections of this Article. Building on the findings of Articles 1 and 2, Article 3 (Chapter 4) empirically addresses the societal and innovation system related influence of different agents on the development of AFI. Based on this, managerial and policy implications for promoting favorable conditions for the development of AFIs and the integration of frugality in innovation processes are elaborated. An overview of the content of Articles 1 to 3, as well as the methodology used and the status of the publication, can be found in Table 1.

1.4.2 Chapter overview and interpretation note

While Chapter 1 provides an introduction about the motivation, the state of research, data, methodology, and the structure of the dissertation, the Articles listed (see Table 1) constitute the main body of this dissertation. Chapter 2 includes a conceptual theoretical consideration of the prerequisites for the development of AFIs from a societal and systemic perspective. Chapter 3 establishes a concept for measuring AFI. Building on the results of the previous Chapters, Chapter 4 provides a first empirical analysis of the influence of systemic agents on advanced frugal product attributes. Finally, Chapter 5 summarizes the findings of this dissertation, suggests policy and managerial implications, and outlines further research needs.

To give the reader a better understanding of this dissertation, two limitations are to be indicated already at this point. First, the author's understanding of AFIs changed during

the course of writing the Articles. This is due to the emerging research field and a change from a narrow definition on specific characteristics to a more general goal-oriented definition. This has already been described in more detail in Chapter 1.2.1. Second, the data used for the analysis refer only to manufacturing companies based in the German federal states of Hesse and Lower Saxony. The market situation described in Chapters 3 and 4, as well as the influence of social agents in Chapter 4, may be different in other industries and states. However, it can be assumed that the influence of individual agents, since customers and the government might be the same, is similar in other industries in Germany. General limitations of the individual Articles are dealt with separately in Chapters 2, 3 and 4. In the following Chapters, the terms advanced economies and industrialized countries/economies are largely used synonymously. In addition to the specific reference to the political territory and the economic area, the use of the terms is also tailored to the readership of the respective journal of the Articles.

CHAPTER TWO

The prospects of advanced frugal innovation in different economies

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Abstract

Existing research on frugal innovations underrates the potential for sustainability that arises from the development of advanced frugal innovations (AFI) and the widespread adoption of frugal design principles. Based on a distinction between advanced and unrefined frugal innovations, this Article examines factors for AFI generation using the concept of innovation systems and the multi-level perspective, and discusses the differences arising from the contexts of emerging and advanced economies. The paper explains which institutional and systemic conditions support the development of advanced frugal innovations. In particular, it discusses the interplay of the actors, a common frugal mindset, and the institutional framework. The way these factors play out depends on the system and transition conditions in advanced and emerging economies. The paper shows that applying the perspective of AFI and frugal design principles opens a new perspective for research on frugal innovation.

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2.1 Introduction

Frugal Innovations achieve cost reductions through significantly reducing the consumption of resources. They address the needs of less affluent customers and significantly contribute to ecological sustainability (Albert, 2019; Rao, 2013; Zeschky et al., 2011). Research throughout the past 10 years has established a widely shared understanding of several common features of frugal innovations, and related studies describe examples of frugal products and discuss potential benefits and risks. However, as Hossain criticizes in a recent contribution (Hossain, 2021a), the field still continues to discuss definitions and case-based observations, instead of moving forward into exploring the full potential of frugal innovation.

Some of the confusion about the meaning and the prospects of frugal innovation, as well as the lack of an established operational concept for empirical research, can be attributed to the multidisciplinary character of the field. Most scholars who have explored the nature and the potential impact of frugal innovations have applied the perspective of international business and management studies, stressing the connection between innovation and serving hitherto under-privileged users in emerging markets (Zeschky et al., 2011). The relatively small number of studies from disciplines other than management usually highlight different aspects of frugal innovations, for example their underlying design principles. For the latter group of contributions, the country context is less important (Rao, 2019; Wohlfart et al., 2016).

A larger part of the confusion, however, is caused by the ambiguity of the term frugal innovation regarding quality and novelty. In the related publications, frugal innovations cover a broad spectrum from low quality innovations (e.g. makeshift, good-enough, improvised innovations) to high quality innovation based on sophisticated engineering (Rao, 2017b; Wohlfart et al., 2016). Regarding novelty, the range is similarly broad. Frugal innovations may be new-to-the-world products with previously unknown product architectures or components, but they may also be re-designed and “frugalized”, versions of products that have long existed (Rao, 2013, 2019). Due to this diversity, this Article focuses primarily on “advanced frugal innovation” (AFI), which will be distinguished from “unrefined frugal innovation” (UFI) in the present Article. This is based on two arguments. Firstly, AFI can be defined more precisely, and secondly, it can be assumed that they combine socio-economic and environmental benefits, which UFI does not assure.

This paper proposes reducing the complexity of the field by categorizing frugal innovations according to their quality, novelty and benefit to society. It argues that a lot can be learned from discussing the resulting categories, i.e. the more narrowly defined types of frugal innovations in the context of the established theoretical concepts of innovation studies and sustainability transitions. Combining these research fields may help to explain difficulties in the development and scaling up of frugal innovation as well as advantages regarding societal and systemic requirements. This helps to uncover the conditions for the generation of frugal innovations and potential benefits that result from a frugal approach to product design. The use of these theoretical perspectives clarifies, in turn, why it makes sense that the related literature continuously stresses the need to focus on different markets and economic contexts.

This paper asks the following research questions:

Research Question 1: What factors that determine the emergence and potential impact of frugal innovations become apparent in the context of "innovation systems" and "multi-level perspectives"?

Research Question 2: How does the development and application of frugal innovation differ between advanced and emerging economies?

Answering both research questions requires reviewing and integrating selected key aspects of the terms and concepts mentioned, at the expense, however, of a comprehensive theoretical discussion and a complete literature review. The paper shows that the prospects of generating and applying frugal innovation vary systematically with country and market contexts. To this end, the paper shows under which circumstances the application of frugal design principles in innovation processes can become established and the emergence of AFIs is favored. This has important consequences for the potential contributions of frugal innovations to sustainable development and related policies.

The remainder of the paper is organized as follows. Chapter 2.2 provides an overview of the existing research and prerequisites for the development of frugal innovation. In addition, we differentiate between unrefined and advanced frugal innovation. Chapter 2.3 introduces the innovation system perspective into the research field, where the importance of the actors and a common mindset is highlighted. Chapter 2.4 elaborates further on the transition conditions, discussing frugal innovation from the

multi-level perspective. The current situation of systemic and transition-related preconditions is considered in Chapter 2.5. This includes a rough overview of the conditions in advanced economies as well as emerging economies. In Chapter 2.6, we relate the conceptual results to the FagusGreCon case study. Finally, Chapter 2.7 discusses and summarizes the results of this work and provides an outlook on the relevance of further research.

2.2 Frugal Innovation: Features, Categories and Perspectives

Most scholars publishing about frugal innovations agree that they share various features that distinguish them from most other innovations. Weyrauch and Herstatt (2016) identify three overarching features, namely substantial cost reduction, concentration on core functionalities and optimized performance level, which Rao (Weyrauch & Herstatt, 2016) already defined in a similar form. Cost reduction means that these products are cheaper alternatives to existing products, a concentration on core functionalities is the result of omitting unnecessary features, and an optimized performance level refers to a product architecture, which includes the ideal coordination of all components (Weyrauch & Herstatt, 2016). These three criteria have been frequently applied as a working definition. A number of publications aim to discuss the nature, the relevance and the broader implications of these features using the example of selected frugal innovations and their attributes (Rao, 2013). Brem et al. (2020) examine the process of making a product according to these characteristics. Other authors approach frugal innovations from the angle of the markets they address and originate from.

There has been a strong research focus on the Bottom of the Pyramid (BoP) and the emerging market context, most frequently explored using the example of India (Prahalad, 2012). In this line of research, frugal innovations are considered to be the result of constraints in terms of customers' limited purchasing power and in terms of innovators' capacities. There is strong evidence that innovations for the BoP in emerging economies are strongly focused on solving local constraints (Sinkovics et al., 2014). The continued growth of BoP markets, however, makes them attractive not only for local firms, but also for firms from advanced economies that are usually considered innovation leaders. However, in order to produce frugal innovations, these companies have to broaden their product perspective and include knowledge about the needs of poor customers (Jha & Krishnan, 2013). Many authors (e.g. Belkadi et al., 2016;

Zeschky et al., 2014) thus emphasize that successful development of frugal innovations requires carrying out local R&D activities in emerging economies. In these cases, access to local culture-related tacit knowledge is of critical importance, as engineers need to understand the needs of the poor (Altmann & Engberg, 2016). Some western companies such as GE, Siemens or Mettler Toledo developed frugal products for emerging markets such as India and China, and their experience shows that these products are also sometimes competitive in western markets (Agarwal & Brem, 2012; Zeschky et al., 2011). Demand for affordable products is increasing among certain customer groups in advanced economies, making high quality frugal products attractive from an affordability perspective in these economies as well (Hossain et al., 2016). In addition, these frugal innovations not only reduce costs, but also foster sustainability (Hossain, 2018; Hossain et al., 2016; Pisoni et al., 2018; Rosca et al., 2017) and can thus make a contribution in emerging and advanced economies (Kroll & Gabriel, 2020).

The latter arguments indicate, however, that high quality frugal innovations are profoundly different from low quality frugal innovations. While the two groups conform to the criteria provided by Weyrauch and Herstatt (Weyrauch & Herstatt, 2016), the exact meaning and the implications of these criteria differ fundamentally, and future research into frugal innovations needs a differentiation according to quality. To denote a key quality-related difference, Rao (Rao, 2013, 2017c) introduced and defined the term "advanced frugal innovation" (AFI). An AFI is based on sophisticated engineering, involving research and development work as well as rigorous design. In the case of AFI, cost reductions and the optimization of performance levels are systematic, rather than the outcome of trial-and-error processes. AFI are suitable for mass production, the range of their applications can be systematically determined and their robustness, environmental impacts, durability etc. can be calculated and guaranteed. The broad spectrum of frugal innovations, however, includes many that are not AFI (see Hossain, 2021; Wohlfart et al., 2016). In the case of low quality frugal innovation, for example innovation that involves improvisation and makeshift components, cost reduction goes hand-in-hand with negative product features. These include, for instance, safety concerns in production and use, negative environmental impacts, or difficulties in scaling up production and maintaining quality standards (Hossain, 2021a; Leliveld & Knorringa, 2018; Wohlfart et al., 2016). For this category of non-AFI frugal innovations, we suggest using the term "unrefined frugal innovation" (UFI). The

common denominator of UFI is neither their origin nor their target market, but rather the fact that they lack a sophisticated research and engineering background and may thus also have a negative impact on users and society.

Table 2: Advanced frugal innovation in comparison to unrefined frugal innovation

	Advanced Frugal Innovation	**Unrefined Frugal Innovation**
Key characteristics	Substantial cost reduction, concentration on core functionalities and optimized performance level	Substantial cost reduction, concentration on core functionalities and optimized performance level
Developer	R&D employees, engineers, technicians in companies or research institutes	Any actor (community-based, private individuals, companies) equipped with ideas and entrepreneurial spirit
Consumers	Cost-conscious consumers, sustainability-conscious consumers	Poor consumers
Input	Advanced materials, advanced technologies, advanced manufacturing techniques, simple design, biomimetic, 4R mechanisms	Use of what is at hand, cheap components and materials, affordable technologies
Development process	Research and development, based on scientific principles, rigorous engineering design	Bricolage, based on trial and error, improvisation
Quality	Good quality, reliable, safe to use, standards can be maintained in large-scale production	Makeshift, good-enough for anticipated use, but not fully reliable and partly unsafe
Frugality achievements	Low-price, sustainability	Low-price, (sustainability from coincidence)

Own elaboration based on Rao (2019, 2017a, 2017b, 2013), Gupta (2013, 2012), Wohlfahrt et al. (2016), Leliveld & Knorringa (2018), Weyrauch & Herstatt (2016)

AFIs provide broader societal benefits than UFIs, as their frugality is expressed not only in competitive prices, but more importantly in sustainability (see Table 2). The decisive factor here is the ability to implement sustainability in product development and to take into account non-monetized negative externalities. Therefore, UFI may result in lower product costs by shifting costs to a non-monetized area. As a result, UFI can create negative externalities that may harm users and the environment due to the unawareness of the inventors and the use of what is at hand. In contrast, the development process of AFI focuses on avoiding superfluous components through design adjustments that enable lower resource consumption (Rao, 2017c). This leads to resource-efficient innovations by using scientific principles as well as advanced materials and technologies in development and manufacturing (Rao, 2017c, 2021). The combination of these factors makes AFI affordable, sustainable and scalable. In

contrast to UFI, AFI are not exclusive to customers at the lower end of the market, but can be found in all market segments and geographies.

While all AFI are of high quality, they may differ in terms of their novelty, which leads to a second important distinction. The Oslo manual, dealing with definitions and measures for innovations in general, differentiates between new-to-the-world innovations, new-to-the-region or new-to-the-industry innovations, and new-to-the-firm innovations (OECD & Eurostat, 2018). Henderson and Clark (Henderson & Clark, 1990) highlight differences between innovations regarding their application of more or less novel components and more or less novel product architectures. The term “user-driven innovation” specifies that innovations need not be based on new technologies at all (Hippel, 1988). Brem and Wolfram (Brem & Wolfram, 2014) understand FI as a management approach that concerns development, production and product management, and enables the reduction of resource consumption in products and services. Therefore, the notion of AFI encompasses both completely new products, e.g. the world’s first portable X-ray machines, and frugalized versions of products that had been established in conventional form long before. The latter products have been redesigned according to frugal principles, and the application of frugal design principles leads to the frugalization of existing products (Rao, 2017c). The frugal design principle emphasizes the importance of simple design, modern manufacturing techniques, modern materials, biomimetic and 4R Mechanisms. The degree to which a conventional product has been frugalized can be calculated and expressed with the factor of frugality (Rao, 2013, 2017c). The factor of frugality can be understood as a guideline for the implementation of frugal design principles, which ensures the sustainability of the product. This makes it apparent that many AFIs do not primarily represent market novelties with new functions, but rather that their innovativeness refers to the application of resource and cost saving techniques for design, production and use. It is hence important to distinguish between a product view of AFI, i.e. advanced frugal innovations that are entirely new products, and a principle view of AFI that denotes the application of the frugal design principle for generating frugalized versions of existing products. Since the frugal design principles can be applied to a limitless range of industries and products, the power of frugality may lie mostly in a widespread application of the frugal design principle.

The differentiation between AFI in terms of new products and AFI in terms of a design principle is of great analytical importance. Applying the product view, AFI are product innovations. Applying the principle view, however, AFI appear to be a combination of an organizational innovation, particularly a design process innovation, and an institutional innovation in terms of the norms accepted and applied. The frugal design principle is closely linked to the mindsets of the people active in AFI (Soni & Krishnan, 2014). Accordingly, the frugal design principle is a necessary input for the development of product innovation as well as the frugalization of existing products that can be considered as AFI. Exploring the nature of the frugal design principle as such is not the focus of this paper, however. Instead, this paper uses the differentiation between the product view and the principle view for the conceptual considerations that follow in Chapters 2.3 and 2.4.

The focus on AFI – in terms of new products and frugalization of existing products – requires revisiting the recent publications and condensing the key features of AFI that will be relevant throughout this Article. These prerequisites are AFI-related, but are also partly prerequisites for UFI.

1a) AFI respond to constraints. As mentioned above, one important type of constraint is the limited income and purchasing power of potential users, which goes hand-in-hand with a focus on sales markets in India as the most prominent example (Prahalad, 2012), but also includes China (Chen & Wen, 2016) and other countries in the Global South. Besides the lower overall wealth levels and the larger numbers of poor customers, constraints in emerging economies relate to infrastructure deficits such as lack of access and permanent availability of electricity (Niroumand et al., 2021). However, physical infrastructure can be important to the success of new products even in developed countries. This is evident, for example, in electric vehicles, which in many areas are more frugal than fuel-powered vehicles, but require new charging infrastructure to be attractive for broad application.

1b) The second important type of constraint follows from the need to make products environmentally sustainable through a reduction of the related consumption of resources and energy. This constraint is increasingly imposed in the form of product-related requirements and public measures to increase the costs of carbon usage. This constraint has a spatial dimension as well, since there is variation in terms of standards

and requirements in the use of fertilizers in agriculture, permissible emissions from motor vehicles etc. (cp Chen and Wen, 2016).

2) Innovation actors that generate AFI turn these constraints into opportunities (cp Niroumand et al., 2021). They do not primarily view these constraints as impediments to business activity, but rather as creating new avenues for product development.

3a) The generation of AFI depends on a set of distinctive resources. A first critical resource needed is technological expertise that comes with science and technology, research and development, and the use of sophisticated equipment. It is what Cohen and Levinthal (1989) along with many scholars building on their work have called absorptive capacity, dynamic capabilities etc. (e.g. Shane, 2000; Teece et al., 1997). Since these capabilities can be understood as peoples' individual skills and knowledge combined to create innovation routines, a qualified workforce capable of applying advanced technologies is fundamental to creating AFI (Rao, 2017b, 2019).

3b) The second resource that is critical to AFI generation is a cultural cognitive component that manifests itself in a frugal mindset (Kroll et al., 2016; Soni & Krishnan, 2014), which is closely tied to specific local contexts and institutional settings. The importance of mindset and its shaping has already been observed by Ananthram and Chan (2019), for example, in the case of jugaad, an India-specific variant of UFI. This mindset, which is of equal importance for AFI, results from the continuous search for alternative solutions that counteract widespread scarcity in a creative way but are functional in terms of customer needs (Ananthram & Chan, 2019; Kroll et al., 2016). In fact, this mindset is not only to be found in poor rural or urban communities, but is also applied in Indian companies and is expressed by a positive attitude towards challenges, which also makes India a good R&D location for MNEs (Aoyama & Parthasarathy, 2012). Indian companies are particularly agile and adaptable to challenges, and frugal design principles are extremely effective when it comes to turning constraints into opportunities (Ananthram & Chan, 2019). In addition to exposure to poverty and material constraints, Soni and Krishnan (2014) highlight the importance of a capability to adapt to institutional voids. This capability is an additional factor that works to the advantage of local companies and explains why UFI and AFI are more likely to be associated with emerging markets in their origins, but are not limited to them. There are well-founded arguments in the related literature pointing out that the formation of a frugal mindset is challenging for Western companies but an

important resource for the development of frugal products (Soni & Krishnan, 2014). Krohn and Herstatt (2018) explain this through a better understanding of cost-conscious customers and their living environment. Nevertheless, frugal design principles are already being used in high-tech industries such as aviation. In order to avoid unnecessary loads and the resulting high costs, this industry systematically strives to reduce the use of materials and to focus on lean design and frugal design principles (Rao, 2019).

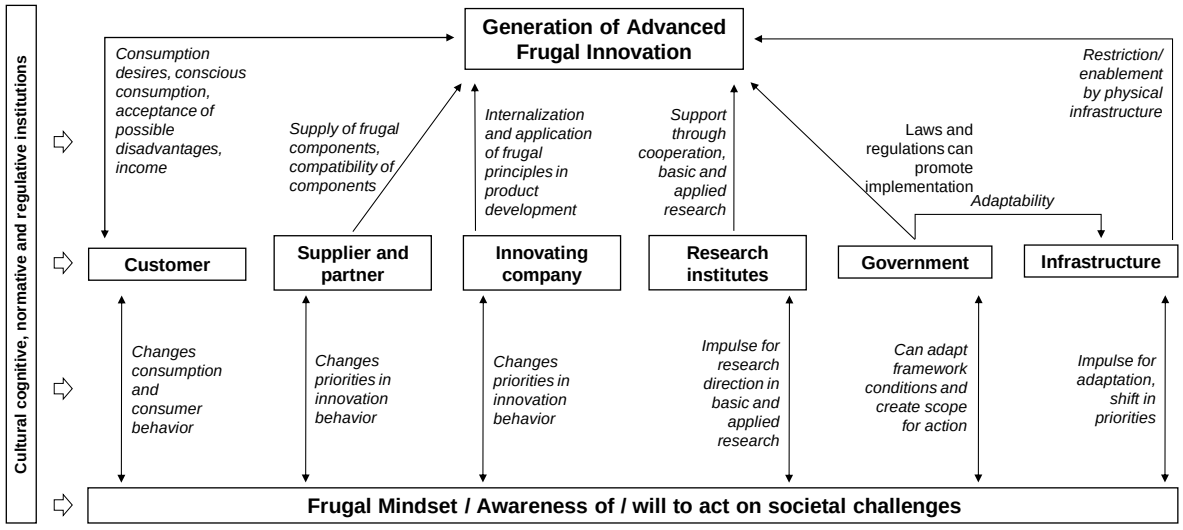
2.3 Advanced Frugal Innovations from an Innovation Systems Perspective

The current state of research listed in Chapter 2.2 makes it clear that systemic prerequisites must be fulfilled for the development of AFI. Since AFI can be viewed as product innovations, the different concepts of innovation systems can be applied as heuristics that help to identify key influencing factors for innovation generation. Inherent to all concepts of innovation systems is the notion that innovations are generated in interactive processes that involve different innovation actors, their interactions, and the institutions that affect actors and their behaviors (Edquist, 1998; Kline & Rosenberg, 1986). This conceptual lens has been applied to National Innovation Systems (Freeman, 1995), Regional Innovation Systems (Cooke et al., 1997), and Technological Innovation Systems (Carlsson & Stankiewicz, 1991). Regardless of the scope of the innovation system examined, the concepts' analytical emphasis is on the factors affecting innovation generation. Relevant actors include the innovating companies and their suppliers, customers, competitors, collaborating universities and other research institutes, banks and ministries (Cooke et al., 1997; Edquist, 1998), while consumers are mainly understood as a source of feedback on innovations (Niroumand et al., 2020, 2021). Interaction between these actors includes exchanges of components, services, finance, and, most importantly, exchange of knowledge. The relevant institutions include norms and routines of communication, collaboration, knowledge sharing etc. (Cooke et al., 1997).

Figure 3 is a simplified graphic representation of an innovation system for AFI. The most important actors are listed in the center of the figure. The selection of important actors is very similar to other products' innovation systems, with the exception of infrastructure, which needs to be included here, since material infrastructure may restrict or broaden the scope for AFI in certain sectors such as transport. Much more

specific to the case of AFI are the types of interactions that affect the process of creating AFI. They are indicated with arrows from the actors in the upper part of the Figure. Specific to AFI are, for example, signals from less wealthy or environmentally conscious customers, specific government regulations, and material infrastructure that facilitates, for example, the use of electric vehicles. The lower part of the Figure indicates the institutions and motives that lead actors to pursue AFI. The items included are motivated from a frugal mindset, i.e. from changes in cultural and cognitive norms that evolve gradually and influence actors' decision-making. Changes in behavior in turn influence the forming of a frugal mindset and the awareness for needs, constraints and opportunities (Rao, 2018, 2019; Zeschky, Widenmayer, et al., 2014).

Figure 3: AFI supporting Innovation System



From an innovation systems perspective, it is not only the specific combination of actors, specificities of the interactions and contributions, and particular institutions that are significant for AFI generation, but also the specific attributes of actors, interactions and institutions. In the case of AFI-generating innovation systems, many actors may be facing resource constraints, depending on their location. As will be highlighted below, in the Indian innovation systems, for example, the numbers of potential actors, e.g. R&D-intensive companies and universities, is limited, as is the workforce with particular skills(Sandhya, 2018). All actors that successfully contribute to AFI generation, however, can be expected to possess profound knowledge in terms of handling scarcity and constraints, and to know ways of responding with frugal ideas. At the level of interactions, what seems most important is that the effectiveness of

interactions depends on many actors that share a similar understanding of constraints, opportunities and frugal solutions. One actor alone will be unable to come up with AFI. And at the level of institutions, it is obvious that a frugal mindset commonly shared, along with priorities, values and norms based on this mindset, will form the system's specific institutional foundation.

Two specifications of innovation systems are of particular interest for AFI: firstly National and Regional Innovation Systems, and secondly Technological Innovation Systems.

The perspective of National and Regional Innovation Systems can provide interesting insights into AFI, since many AFI enablers are regionally determined or influenced by place-specific factors, such as mindset, environment and knowledge. The frugal mindset can be particularly related to local experiences. Effects of climate change, water shortages, pollution and poverty are all space-related. Due to everyday confrontation (e.g. poverty, recurring water shortages) or isolated shocks (e.g. flood, resource-related price volatility), particular mindsets evolve in the affected regions and countries, which may subsequently embrace frugal solutions. Related studies suggest that local institutions have an impact on the type of technological development related to a local context (Bergek et al., 2015; Wirth et al., 2013), which was also observed to be an important factor in the case of UFI and AFI (Pisoni et al., 2018). This refers to cultural-cognitive institutions as well as normative and regulative institutions, and may include habits, but also common attitudes toward political, social and technological developments, which are shared by entrepreneurs, employees, politicians and investors in a region or nation (Martin, 2000; Scott, 2014). Accordingly, it is reasonable to assume that a strong regional awareness of scarcities and constraints as well as environmental awareness can lead to an institutional setting that favors the adoption of frugal design principles in National and Regional Innovation Systems. These can be reflected in consumer behavior, the type of products consumed and their production, as well as in laws and regulations (CO_2 taxes, emissions trading). According to Coenen et al. (2012), a territorial-related frugal mindset can be seen as a comparative advantage regarding the development of frugal technologies and products in this rationale. As actors are interconnected on a regional or national level through fora, clubs, networks and partnerships, the common value system simplifies the flow of information and increases the efficiency of communication (Cooke et al., 1997). These

different proximities influence the extent of the commonalities of these actors and promotes their ability to collaborate and innovate in this way (Boschma, 2005).

However, resource scarcities can also be related to specific industries and the technologies they use. This means that a common frugal mindset is not only related to actors in a certain region, but can also exist within the scope of a Technological Innovation System (TIS). The relevance of TIS is expressed in particular by the fact that, in contrast to UFI, AFI requires advanced technologies to enable, for example, the frugalization of a product. A single region alone is unlikely to have the capabilities to fully develop them. Consequently, cross-regional innovation activities must also be taken into account for the development of AFI. In this context, TIS can create a link between different territorial innovation systems and actors in specific technological fields (Binz et al., 2014; Coenen et al., 2012). In this way, actors from different regions collaborate to create frugal technologies and products. It is important to emphasize that a common vision for the technology field must exist (Markard & Truffer, 2008) and is expressed in the case of AFI by the aforementioned frugal mindset.

From a technological perspective, cooperation with appropriate actors is necessary for a comprehensive exploitation of frugality levels. In addition to the common frugality mindset, the capabilities on which the innovators can draw are a crucial condition that can lead to a distinction between AFI and UFI. While the pure omission of unnecessary components is a comparatively simple cost reduction measure that can also be carried out by a single company, a more comprehensive framework of technological capabilities is necessary to take the sustainability perspective into account. This is particularly evident in the application of 4R mechanisms such as circular economy or the provision and development of new technologies and materials. These are technology-specific, which makes embedding them in an appropriate technological environment crucial.

If this is present, the functions of the TIS (Hekkert et al., 2007) can be an important element in the implementation and establishment of AFI. The importance of the entrepreneurial activity is high, since companies have to implement the frugal design principles as an intermediary between the different conditions. From the knowledge perspective, the TIS network can contribute to a better dissemination of frugal design principles and to the exchange of suitable methods and adjustment of these to the specific context of advanced frugal technologies. It should be noted, however, that the

transfer of frugal design principles, such as the factor of frugality (Rao, 2019, 2020), tends to be classified as codified knowledge, while the application-based methods also include tacit knowledge. Finally, when it comes to concrete implementation, the importance of both the development of new knowledge and the guidance of the search between different technologies is likely to vary according to the forms of knowledge. Of particular interest are the functions of market formation and technology legitimization. In particular, since AFI involves adaptation in design, for example, luxury-related components, a sound knowledge of the market situation and of potential customer groups and their needs must be available (Krohn & Herstatt, 2018; Rao, 2020) and the legitimacy of the changes must be convincingly explained. Since a TIS can help to legitimize and establish a technology in the market (Hekkert et al., 2007), the TIS can be crucial for establishing AFI on larger scales beyond individual territories.

Concluding from the territorial and technological perspective on AFI, it may be useful to consider their emergence on multiple scales. While a National innovation system can be large enough to provide a space for individual technologies and products to develop beyond the niche level (Fuenfschilling & Binz, 2018; Raven et al., 2012), this is not the case for all technologies. Actors must act on different levels and scales to create necessary conditions for the implementation of their innovation (Coenen et al., 2012). However, the importance of the individual level may change over time (Dewald & Fromhold-Eisebith, 2015). As an example, technology standards that influence technology development paths (Rycroft & Kash, 2002) are not decided at the local level. Accordingly, these can also limit the development of AFIs because frugal technologies cannot be applied. Furthermore, institutional factors such as laws and regulations can also change on different scales and may need to be adapted for the development of AFI. In particular, policies aimed at mitigating climate change, such as emissions trading and the associated shortage of emitable CO_2, could provide incentives at the national and international level that favor the development of AFIs. Accordingly, it is useful to consider the application of frugal design principles from a multi-scalar perspective (Binz & Truffer, 2017).

This Chapter has shown that the perspective of innovation systems is helpful for structuring our understanding of the systemic conditions that facilitate the emergence of frugal products and frugal technologies. The basic element is a supportive institutional framework that encourages consumer acceptance of AFI as well as legal

and regulatory requirements that together create incentives for entrepreneurial activity in the development of AFI. Individual companies have a certain but limited scope of action within which they can increase the frugality of their products. In a connected economy with the increasing complexity of products, the dependency on the systemic environment is of great importance. Accordingly, the development and implementation of AFI is simplified if its basic principles are shared collectively in the innovation system. The innovation system offers a framework in which the advanced frugality of products can be fully exploited. Within the framework of interaction in the system, the necessary knowledge modules and skills can be combined, which would not be possible for individual actors. In this context, integration into an innovation system with a shared frugal mindset, thus emphasizing both sustainability and cost reduction, can be seen as a sufficient condition for the development of AFI compared to UFI. The discussion of consequences can be better guided, however, with the help of the multi-level perspective (MLP) outlined in the following Chapter.

2.4 Advanced Frugal Innovation from the Multi-Level Perspective

The system perspective presented in the previous Chapter is useful for discussing the conditions under which frugal technologies emerge. However, the question of the adoption, scaling-up and widespread diffusion of AFI, along with the question of whether and how AFI may be established as a generally accepted principle for the development of new technologies and products, remains unanswered (Liefner et al., 2020). Since the multi-level perspective provides a framework for explaining the sustainability transitions of established socio-technical regimes, it also allows the derivation of conceptual insights into the potential of AFI. Furthermore, assumptions can be made about the conditions under which frugal design principles are applied in innovation processes.

The multi-level perspective (MLP) draws attention to the process of a fundamental and long-term technological change, examining interrelated processes at the levels of regimes, niches and landscape. Socio-technical regimes represent the predominant organizational as well as cognitive routines and rules shared by engineers and firms, norms, established products and technologies, stock of knowledge, etc. with regard to technological development (Geels, 2002; Markard & Truffer, 2008; Nelson & Winter, 1982). Since this also includes a common vision of future technological developments, a technological regime also has a common technological trajectory that leads to

incremental innovations and represents a barrier against radical innovations (Geels, 2002; Markard & Truffer, 2008). Although in some cases a frugalized version of an existing technology may appear to be an incremental innovation, the diffusion of the frugal design principle as an overarching guideline for product development would clearly be a radical change of direction (Rao, 2013). The MLP states that radical innovations are created in niches, which represent a partitioned area inside a regime. Niches provide a protected space against the dominance of the regime. Technologies in a niche are usually not yet mature, and would not be successful in the normal market. The niches offer conditions that do not correspond to the normal market, and offer the technology the opportunity to mature and to create the necessary network of supporters. From this incubation space, some innovations are able to penetrate the regime and change it (Geels, 2002). Finally, for transition, the concept of landscape is crucial. The success and establishment of new technologies from the niche in the regime are strongly related to changes at the landscape level which create an opportunity (Geels, 2002; Kemp et al., 2001). The socio-technical landscape represents a context in which the regimes and niches are located. This encompasses overarching trends that have an influence on the development and establishment of technologies (Geels, 2002). According to Geels (2002), these external factors can include wars, economic growth, and cultural and normative as well as environmental problems. Environmental problems in particular can be considered a crucial landscape factor which may require the use of frugal design principles and thus also encourage the development of AFIs.

The MLP is relevant in the context of AFI, especially with regard to the application of frugal design principles. In the terminology of MLP, frugal design principles can be classified as rules of engineering practice which make a contribution to the structure of a socio-technical regime (Rip & Kemp, 1998). These are applicable across all sectors and technologies (Rao, 2019), and are therefore not limited to specific socio-technical regimes. So far, there is no empirical evidence on the application of frugal design principles on the regime level in different sectors. Rao (2019, 2017a, 2017b) mentions the aerospace, healthcare and automotive industries as areas in which these principles are already being applied. Aerospace in particular is a good example, as every kilogram here generates additional costs in use. To avoid this, a great emphasis in this sector is placed on functional design and the application of modern technologies to reduce the weight and consumption of resources (see Rao, 2021, 2017b). However,

consumer behavior, especially in the advanced economies, e.g. the consideration of unnecessary amenities such as heated steering wheels or heated seats in vehicles, gives reason to believe that frugal design principles are a fixed rule in very few sectors. This is particularly evident in the fact that scarcity was not a ubiquitous problem in advanced economies in recent decades, a situation that has changed in recent years. Accordingly, the conditions under which frugal design principles are applied and rise from niches to an established rule at regime level in different sectors are particularly relevant.

It can be assumed that the transition process for establishing frugal design principles in different sectors has similar scarcity-related origins, but different speeds. Particularly in regimes with more complex and rigid standards, regulations and routines, etc., their implementation is likely to be inhibited. Accordingly, it is to be expected that the implementation of frugal design principles as a rule of engineering practice in sectors of the emerging economies will be easier to establish than in the advanced economies (discussed in more detail in Chapter 2.5).

It can be assumed that in most sectors, especially in the advanced economies, frugal design principles will initially be applied in local niches. This can be theoretically deduced, although no empirical evidence supports it so far. Following the innovation systems perspective (see Chapter 2.3), it can be assumed that a group of actors can represent a niche in which frugal design principles are applied and advanced frugal technologies can emerge and mature based on their frugal mindset. For example, this can be a combination of resource-conscious consumers and companies that are able to satisfy this awareness. Another example is the product diversification of companies that offer frugalized products for the emerging economies in addition to their normal product portfolio for the advanced economies (e.g. Zeschky et al., 2011). This is supported by Coenen et al. (2012), who argue that transition is based on the shift in the socio-cognitive orientation of actors in social and economic processes that can lead to change at different levels. As already argued, it can be assumed that this socio-cognitive shift to a frugal mindset will initially prevail primarily regionally or among individual actors. Schot and Geels (Schot & Geels, 2007) argue that these actors' cognitive, social and spatial distance from regime actors leads to isolation in the niches, as they are not considered relevant to the market. Spatial isolation is argued to be related to the existence of spatially specific conditions. In the context of AFI, local

scarcities, which may result in the emergence of a frugal mindset, can be regarded as precisely these conditions. Due to the nature of frugal design principles, as a response to limitations, this should not differ between sectors.

In the case of AFIs, landscape conditions that demand resource saving and competitive prices may destabilize a regime in a way that reveals the necessity or opportunity to apply frugal design principles. Low income, for instance, is a societal condition that can cause companies to apply frugal design principles to serve these consumers (Hossain, 2020), in particular when inequality and inclusive growth rank high in domestic and international public debates (George et al., 2012). This may explain why India, due to the high proportion of low income households, is considered a major innovator of frugal products, and the place where frugal design became visible (Tiwari & Herstatt, 2012). The high proportion of low-income households in emerging markets makes product cost reduction a primary goal, while sustainability is a secondary one, as it is less urgent in a direct comparison. These differences in urgency also explain the coexistence of AFI and UFI. In particular, cost pressure can lead inventors to develop UFIs because sustainability is not yet considered relevant enough or knowledge and ability are not sufficient to take both into account.

A second factor that can bring about a huge shift in the socio-technical landscape is climate change and environmental pollution (chemicals, plastics etc.). Climate change may stimulate the adoption of innovation behavior and the pursuit of frugal design principles. On the one hand, changing climatic conditions, such as increasing water shortages and droughts, create the need to achieve the same output with reduced resources. On the other hand, climate change mitigation measures are also geared to artificial scarcity, such as the targeted reduction of greenhouse gas emissions. In this context, the application of frugal design principles can be an attractive way to make products more sustainable, while considering acceptable prices. This means that supply capacity for broad sections of society can also be maintained or newly created in this context. Accordingly, it can be assumed that in the future, frugal design principles could also be increasingly applied in the development of products and technologies in advanced economies.

The emergence of frugal products and technologies in innovation systems as niches, in combination with landscape conditions, can be an explanatory approach for the application and diffusion of frugal design principles and transition towards more

frugality in economies and societies. While it can be assumed that the reasons for pursuing frugal design principles can be different in various systems and scales, the landscape level can be seen as an essential transition criterion, since changes are able to destabilize existing regimes (Geels & Schot, 2007) and thus create scope for the implementation of frugal design principles in innovation processes. The changes on the landscape level can diversify the institutional framework, which is in general decisive for the establishment of technologies in different regimes (Coenen et al., 2010), and thus support the application of frugal design principles, technologies and products beyond the niche level. These include trends that shape collective problem awareness and mindset due to increasing constraints, which include those pertaining to resources and energy, enforced through individual behaviors or even laws and regulations. Accordingly, in a changed environment, it may be an economic and societal necessity to establish frugal design principles at the regime level.

It is thus important to highlight that the constraints which form a basis for the application of frugal design principles and AFI generation also play out at the niche and landscape levels. In this context, recognizing opportunities related to constraints is part of the dynamics in niches, and building relevant resources in terms of technical abilities as well as mindsets is a niche-level process as well.

2.5 Conditions for AFI in emerging and advanced economies

This paper's previous Chapters have defined the meaning of AFI and discussed how the notion of AFI can be examined from the angles of the pertinent concepts of innovation systems and sustainability transitions. This discussion had to be focused mainly on a theoretical point of view. Another constitutive element of the term AFI, however, is its emergence from emerging market contexts. The term frugal innovation was originally coined with respect to innovation originating in India (Krishnan & Prashantham, 2019), and analyses have shown that Western multinationals relocate to emerging markets to tap into their innovative capabilities for AFIs (Soni & Krishnan, 2014; Zeschky, Widenmayer, et al., 2014). Despite a number of examples of AFI from advanced economies (Rao, 2013; Wohlfart et al., 2021), the notion of AFI is still strongly connected to India and the emerging markets context.

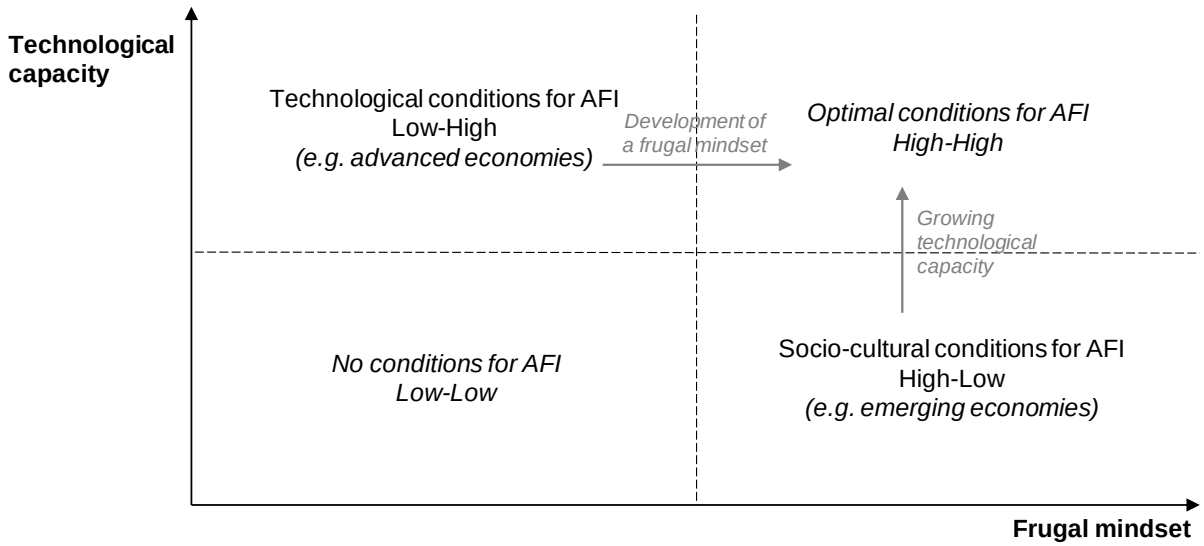
Hence, a conceptual examination of AFI in the light of innovation systems and sustainability transitions must include a consideration of place-related factors on the

global scale. This Chapter discusses a number of preliminary insights that follow from combining the evidence about the role of places and national conditions for AFI with the concepts considered above.

Innovation systems concepts generally stress the importance of factors affecting the generation of innovations, notably innovation actors' capabilities and interactions, and favorable institutions. Regarding actors' technological capabilities, locations in emerging markets usually find themselves in a difficult position (Viotti, 2002). In emerging markets, only a limited number of innovation actors exist that are capable of carrying out systematic and high-level engineering R&D. In the case of India, for example, only a few companies such as the Tata Group or Serum Institute of India are equipped with sophisticated R&D facilities, and a similar pattern characterizes India's public S&T sector, which only hosts a limited number of globally significant institutions, most importantly the Indian Institutes of Technology (IIT) (cp Chidambaram, 2011; Tiwari and Herstatt, 2012) and Indian Institutes of Science (IISc). In comparison, moreover, corporate R&D in India focuses primarily on development and less on research (Krishnan & Prashantham, 2019). In recent years, however, the Indian government has stepped up its efforts, particularly in expanding IITs, and many MNEs have expanded their R&D activities in India (Krishnan & Prashantham, 2019), as they provide a good R&D environment for products for the BoP (Aoyama & Parthasarathy, 2012). Although the ability of companies to generate AFI is increasing, the very limited number of actors who actually generate AFI - with the emphasis on A - is only increasing slowly. In this context, the small number of truly technology-oriented innovation actors limits not only the number of potential innovators, but also the scope for interactive innovation processes. China is an important exception among the emerging economies (Losacker & Liefner, 2020), having built impressive industrial and innovative capacities (Zhou et al., 2016), while most economies in the Global South struggle to strengthen their S&T and R&D capabilities. The major advantage of countries such as India, however, is obviously the presence of knowledge related to understanding the needs of the poor. This particular knowledge is a place-based asset, which, however, cannot be fully exploited for AFI due to the bottlenecks in terms of technological capabilities. The ability to understand the needs of the poor and the resulting opportunities has thus resulted in remarkable activities of small firms with inferior R&D capabilities that generate UFI in a makeshift and improvised way (e.g.

Cohen and Levinthal, 1989). Their innovations address poor customers' needs but can hardly be scaled up for broader use (Smith et al., 2016), and may have inconsistent environmental effects. This situation may improve in the long run if the state continues investing in education, science and the technological upgrading of firms (Humphrey & Schmitz, 2002). Whether such an expansion of capabilities would immediately benefit AFI generation is not certain, however. The Chinese example shows that there is an inherent tendency during upgrading processes to concentrate increasingly on serving advanced economies and striving for technological excellence (Kroll & Liefner, 2021).

Figure 4: Interaction of frugal mindset and technological capacity



Innovation actors' technological capabilities for generating AFI are more conducive in advanced economies that host strong and diversified innovation systems. On the other hand, however, actors in these economies lack a true understanding of the needs of the poor, which is the main reason for MNCs to invest in India. The limited knowledge of researchers and engineers in advanced economies, and also a reluctance to shift the focus of product design from prioritizing performance alone towards applying a frugal design, are viewed as existing barriers.

Linkages in innovation systems and the institutions governing these linkages benefit when many collaborating actors command comparable capabilities and share a compatible mindset. In this context, the coexistence of a frugal mindset and technological conditions is necessary for the development of AFI (see Figure 4). The innovation systems of advanced economies benefit from shared technological

capabilities but remain restricted in terms of AFIs as long as knowledge about frugality and a corresponding mindset are rare. On the contrary, a common knowledge about constraints and a frugality-oriented mindset may increase the effectiveness of linkages in emerging economies' innovation systems, while a lack of technical capabilities may appear to be a crucial bottleneck. Accordingly, the conditions for applying frugal design principles in innovation processes in emerging und advanced economies are contrary to one another, but also unequally distributed. For the broad application of frugal principles, technological capabilities would have to be further developed in the emerging economies, while in the advanced economies, the development of a culture supporting frugality appears to be necessary. Concepts of sustainability transitions such as the MLP tend to focus less on the conditions for generating innovation and more on the influence of successful innovations on society as a whole. According to these concepts, the prospects for a fast adoption and scaling-up of AFI depend on different factors, most importantly supply-side conditions, local demands and institutions. In emerging economies, a supply-side bottleneck regarding innovation capabilities has been mentioned above; and with respect to production capabilities, this bottleneck may be less pronounced. The MLP centers on the conditions at niche level and at landscape level, and on the question of how these relate to the stability of the existing regime. Poverty, climate change and related changes in the availability of resources shape societies as a whole, weaken existing regimes and may bring about a change towards more frugality. As of today, these factors seem to affect emerging economies more strongly (Roppelt et al., 2021; Zeschky et al., 2011) and advanced economies less. India, for example, suffers from persistent poverty and from high levels of pollution (Gandenberger et al., 2020; Tiwari & Herstatt, 2012), which can lead to an everyday increase in awareness of both problems and the application of frugal design principles. Although these problems are of a different magnitude in advanced economies, it can be predicted that as climate change progresses, awareness may also increase in advanced economies and lead to a mindset shift. Subsequently, frugal design principles may gain in importance. However, challenging regimes requires overcoming interrelated barriers regarding technology, infrastructure, institutions and policy.

Both emerging and advanced economies today depend on technologies that belong to a carbon paradigm (Unruh, 2000). The conditions for accepting AFI alternatives, however, may still be very different between the two types of economies. In countries

such as India, the material infrastructure is not fully developed in all parts of the country, urbanization is an ongoing process, education is still expanding etc., and these dynamics provide growth opportunities for a frugal regime without the immediate need to downsize or abandon those parts of the economy that are already established based on old technologies. An AFI-based economy may hence emerge, in niches and to some degree beyond niches, without creating enormous social tensions. In emerging economies, moreover, one can expect a greater openness of the public towards frugal solutions in general, as these societies are more aware of the need to integrate pro-poor technologies (Rao, 2014). Furthermore, the conventional technologies used in emerging economies are adapted versions of advanced-country technologies that were originally inappropriate, at least with the factor conditions under which they were generated (Kaplinsky, 2011). Demand for AFI will thus be present in emerging economies, with many poor customers, as well as limited budgets of companies and state organizations that generally minimize their options to use expensive advanced-country products.

In this context, emerging economies face the enormous challenge of combining the inclusion of small households (Kroll & Neuhäusler, 2019) and sustainability. AFIs are an adequate solution. However, ecological sustainability and the needs of people with lower incomes must be considered equally important. It is likely, however, that the servicing of people with low incomes is often given higher priority in emerging economies as a more obvious and short-term goal, and may thus encourage the emergence of UFIs. Regime-level forces cannot ignore the needs of large segments of relatively poor/backward actors, which is why technological regimes in countries such as India focus much more on balancing intentions and needs and on poverty-related issues than regimes in advanced economies. In advanced economies, barriers against AFI at the regime level may be stronger. The interplay of existing technologies displaying a desire for performance and perfection, in accordance with supply and demand-side actors, institutions and infrastructure, has been evolving undisputedly over decades. The growing public awareness of the need to change is unidimensional and related to environmentally friendly technologies, while serving the demands of less wealthy populations plays no role. The most obvious way to align the conventional innovation paradigm with the need to become climate neutral is developing and using new technologies, building a competitive lead in these technologies and generating wealth from green tech industries (Trippl et al., 2020). This development is not a

deviation from the intention to use innovation for performance optimization, and it is far from using innovation to optimize overall resource consumption. Developed-country customers that ask for AFI can be expected to remain niche, at least in the near future.

Table 3: The regional generation-application paradox of AFI

	Advanced Economies	**Emerging Economies**
Innovation Systems Perspective		
Actors	Technologically strong, but lacking particular knowledge about poverty-related constraints	Technologically weak in comparison, but equipped with relevant knowledge and experience
Interactions	Good availability of capable partners	Limited availability of capable partners
Institutions	Environmentally conscious but not regarding poverty	Favorable with respect to both environment and poverty
Multi-level Perspective		
Niche	Emerging environmental awareness and activity	Both environmental and poverty-related awareness
Sectoral Regimes	Mostly carbon-centered, often stable in norms and standards, mainly high-tech and growth-oriented	Mostly carbon-centered, less stable in norms and standards due to existence of institutional voids and existence of grassroots attempts to change
Landscape	global environmental pressure	global environmental pressure and domestic poverty-related pressure

Hence, integrating the notion of AFI into the contexts of innovation systems and sustainability transitions while taking into account the particular conditions of advanced economies and emerging economies reveals a paradox (see Table 3). Countries such as India, where UFIs were discovered, do not necessarily provide the most suitable innovation-systems-conditions for generating AFI. They are in a more favorable position, however, when it comes scaling up AFI and changes at the regime level. Their advantage, as discussed in the early studies of this field, is mainly related to UFI, which are not advanced in technical terms and will not have a significant long-term impact. Advanced economies provide conditions conducive to generating AFI at the innovation systems level, with the major bottleneck, however, being a lack understanding of poor peoples' needs and the intention to focus on them. Important barriers towards a widespread diffusion of AFI can, however, be assumed to exist at the regime level. This pattern will have strong effects on the prospects and promises of AFI regarding their potential contribution to sustainability. This paradox hence seems to explain a large part of what Hossain (2021) has observed as a dissatisfying state of the related debate.

2.6 The case of FagusGreCon

The company FagusGreCon was selected as an illustrative case study to demonstrate this paper's conceptual considerations. FagusGreCon has a diversified product portfolio in fire prevention that is differentiated for advanced and emerging economies and uses frugal design principles in its product development. The case illustrates the influence of system actors as well as institutional conditions in different regimes for the development of frugal features in product design. Initially, FagusGreCon was contacted in the context of research into corporate innovation and investment strategies in October 2020. In September 2021, we initiated a group discussion on the potential of AFI for German companies at the Lower Saxony Business Association, where companies such as FagusGreCon were also represented. The findings of this group discussion are part of this case study. For this purpose, we conducted in-depth interviews in December 2021 and January 2022, complemented with further information collected from documents and several product data sheets.

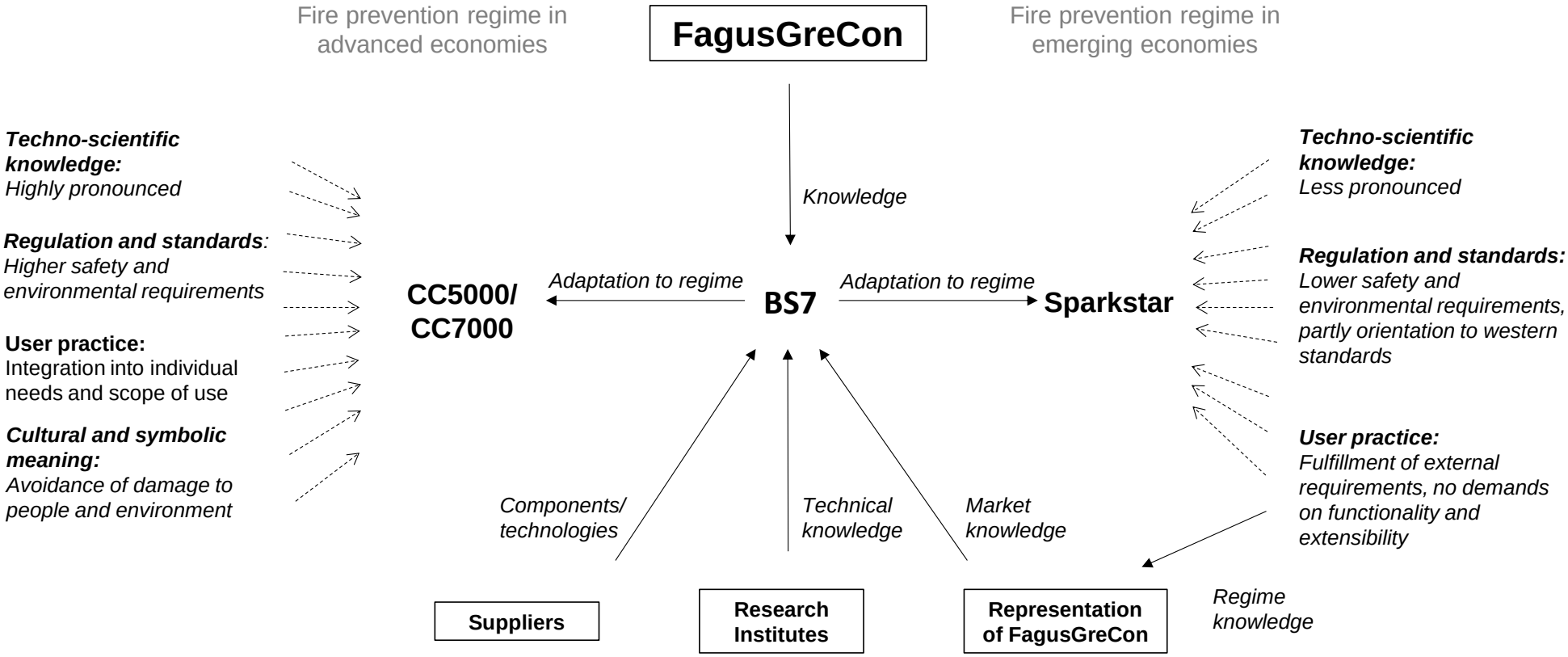
As a global market leader, FagusGreCon employs around 700 people and operates in both advanced and emerging economies with an export share of around 80%. FagusGreCon emphasizes the high quality of its products and invests about 10% of its turnover in R&D. The largest division is fire prevention equipment, which is used in several industries. The spark protection technology BS7 is the basis of this case study, as it is used in different designs for developed as well as emerging markets. BS7 is a technology that makes it possible to prevent and extinguish fires in production facilities. The technology includes a sensor that monitors the flow of material inside a pipe, an extinguishing element and a control center. The control center coordinates the detection and extinguishing of fire hazards such as sparks and embers. The sensor and extinguishing element are almost identical in all products in emerging and advanced economies. Differences exist mainly in the software center, which monitors the material flow and coordinates the extinguishing process.

To illustrate the conceptual elaborations of this paper, three aspects are discussed below: firstly the existence of a frugal mindset and classification of BS7 as AFI, secondly the influence of innovation system actors, and thirdly the impact of market-related institutions on frugality.

The frugal mindset that can be attributed to FagusGreCon is one of the key factors influencing the actual design of BS7 technology in different products. FagusGreCon places emphasis on a simple design in all its products with the aim of saving resources and costs and ensuring a higher robustness. Another goal is the simplicity of use, which should be possible without special qualifications. Furthermore, the company tries to use mainly reusable and recycled materials and almost exclusively water for extinguishing. These fundamental principles can be assigned to the frugal design principles and are also predominantly demanded for the factor of frugality (Rao, 2017c, 2019).

Although the company's ability to design is significant, the extent of frugal characteristics is both limited and supported by the innovation system and regime structures (see Figure 3). FagusGreCon's entrepreneurial activity can be classified as a mediating role, applying its own frugal mindset to its products, but bringing it into line with the knowledge and technologies of the innovation system and adapting it to different regime conditions of the markets. As a result, products based on BS7 technology differ in the frugality dimensions of cost and sustainability depending on the market. However, the actors of the innovation system that provide knowledge and technologies for the products of both markets are the same, and interactions with suppliers and research institutes are found to be important. The research institutes have a knowledge-building effect and, in the case of FagusGreCon, offer insights into the resource-efficient use of extinguishing mediums. In cooperation with two German universities, the amount and substance of extinguishing agents used to extinguish different materials is being investigated. The aim is to avoid unnecessarily large amounts of harmful substances in order to protect the user's production. The role of suppliers is to transfer knowledge by providing technological components needed for BS7. However, the components supplied are not developed under frugal design principles, so the frugality of the technology and products based on it decreases. FagusGreCon does not have the market power to assert its own interests against suppliers. If frugal design principles were applied by the suppliers, this would have a corresponding effect on the frugality of FagusGreCon's products. Currently, FagusGreCon mainly purchases standard components from its suppliers, which are frugal in the sense of lower cost, but do not correspond to the frugal company philosophy, which means a higher use of resources.

Figure 5: Regime integration pressure of BS7 technology



The effects of given institutions, which differ in particular between markets, can be highlighted in the context of regime structures. In response to socio-technical conditions, the company's scope for action is limited and must be adapted to markets and regimes in advanced and emerging economies. In the advanced economies, the demand for fire prevention systems is mainly based on the prevention of the loss of production capability and the associated competitiveness. In a symbolic meaning, the purchase of fire prevention systems means the prevention of damage to people and the environment, which can cause enormous damage to the image of the manufacturing companies. Accordingly, customers of fire prevention systems attach great importance to the accuracy of fit and the extent of integration into their production process. This requires a certain intelligence of the systems as well as adaptability. FagusGreCon responds to these market needs with their products CC5000 and CC7000. The difference between them lies mainly in the number of fire prevention lines that the respective system can monitor. The decisive factor here is the modularity of the two product types, where individual components can be subsequently replaced or supplemented in order to optimize the performance level to the specific needs of the customer. This not only reduces the use of resources and unnecessary waste by replacing complete systems, but also reduces costs while guaranteeing quality (Agard & Bassetto, 2013; Sharma & Iyer, 2012). This in turn supports the frugality of the product. Another aspect is the existing standards and regulations. Since fire prevention involves safety technologies, insurers, for example, insist on the use of more extinguishing material than necessary to cover as many individual cases as possible with one guideline. This in turn increases the use of resources and reduces frugality. This is partly contrary to the situation in many emerging economies, for which a further product based on BS7 technology with adapted properties was developed for this reason. A more frugal technology, the Sparkstar, was developed to fit the fire prevention regime in emerging economies. The decisive knowledge about regime conditions needed for developing the Sparkstar is transferred by a local representation for the emerging economies. Compared to advanced economies, fire prevention systems are less common in production facilities in emerging economies. In some cases, the authorities prescribe the use of such devices, which in turn are based on international standards. More important, however, is the influence of supply chain regulations from advanced economies that require appropriate fire prevention measures. The need for these precautions to protect people and the environment is

not yet widely shared in the emerging economy regime. In practice, this means that most companies only fulfill the minimum safety requirements. For example, "in the Chinese market […] customers actually want to see nothing of their plant and have it run in the background" [FagusGreCon]. Accordingly, significantly fewer functions are demanded, which reduces the products' technological sophistication and thus also the price of the product, which increases frugality. On the other hand, since the Sparkstar has significantly less intelligence, it cannot simply be expanded on a modular basis, which then involves higher resource consumption.

The BS7 technology illustrates the concept described in the previous Chapters. It can be seen that although the company has a frugal mindset and follows frugal design principles, the final level and dimensions of manifestation of frugality of the products depend on additional factors. While in the advanced economies, products based on BS7 technology tend to achieve advancements by frugality in sustainability, the cost dimension is more pronounced in the emerging economies. It can be seen that there is still potential in reducing resources and increasing the level of frugality, which is currently due to the lack of application of frugal design principles by all actors. At the same time, it can be seen that the legitimacy of these characteristics is different in the two regimes, and that both frugality-promoting and inhibiting factors are present. While the technological capabilities for AFI are available in the advanced economies, as already described in Chapter 5, there is a lack of a frugal mindset in some cases. This is more pronounced in the emerging economies, but only with regard to the cost perspective, while the aspect of sustainability is sometimes neglected.

2.7 Discussion and conclusion

Advanced frugal innovation offers a way to address current global challenges. However, the necessary broad application of frugal design principles in business is fraught with complex obstacles. This particularly includes the fuzziness of the term FI, which may deter companies from considering the AFI option, and which this paper attempts to counter by differentiating between AFI and UFI. Regardless of this differentiation, however, systemic and transition-related factors determine the broad emergence and potential impact of FI in different economies. The factors that lead to this were the object of investigation of research question 1 and were answered from the perspective of innovation systems and MLP with regard to AFI. Research question

2 focused on the innovation-related differences between emerging and advanced economies in the application and development of AFI.

From the results of this work, four factors emerged as particularly relevant with regard to research question 1. Firstly, a frugal mindset as well as the associated institutional framework can be seen as a significant factor for the application and acceptance of frugal design principles and ultimately the development of AFIs. Secondly, this mindset must be shared by multiple actors in an innovation system and may be expressed in the consumption, support and development of their own advanced frugal products and product components as well as in the provision of necessary knowledge (e.g. appropriate methods), resources (e.g. appropriate materials) and technology-related frugality-enhancing infrastructure (e.g. circular economy). Thirdly, it can be assumed that AFIs emerge in innovation systems especially when they have to respond to scarcities that entail the application of frugal design principles and when they form in a niche. Fourthly, the emergence of new or the awareness of existing scarcities can lead to the rise of frugal design principles to the regime level. It can be assumed that climate change and policies to combat it will provide a favorable framework.

However, in the work on research question 2, it became apparent that these factors differ greatly between emerging and advanced economies. The systemic prerequisites in the advanced economies are significantly more pronounced than in the emerging economies due to existing networks and a large number of specialized participants as well as the corresponding research capacities. Conversely, this can be observed when the transition criteria are taken into account. It can be assumed that these are much more pronounced in emerging economies, which is likely to be due in particular to an obvious confrontation with financial shortages and environmental pollution. Both advanced and emerging economies thus fulfill part of the precondition for the emergence of AFIs that are mirrored in firm-level competitive advantages. However, this pattern could be overturned if emerging economies catch up even further with research capabilities or advanced economies face greater constraints.

Specific recommendations for the development of AFIs can already be derived from the research findings at this point. However, in line with the different conditions at the outset, these differ between emerging and advanced economies.

Advanced economies have to carry out more awareness-building and competence-building measures. Awareness-building measures in the advanced economies can generate a more pronounced understanding of the existence of scarcities and thus increase the acceptance of AFIs. This includes both the monetization of negative externalities, such as the emission of greenhouse gases and hazardous substances, and the adaptation of standardization and the introduction of limits. These can make society aware of latent scarcities and at the same time create pressure to adapt. However, since there is also a lack of knowledge about the application of frugal design principles in product design, the measures mentioned must also be accompanied by competence-building measures. It is obvious to integrate knowledge about frugal design principles into engineering education, which will then carry them into the companies (Liefner et al., 2020). From the perspective of the companies, it may also make sense to work specifically with actors from the emerging economies in order to be able to access the corresponding skills. Various authors have already suggested this in this context (e.g. Belkadi et al., 2016; Zeschky et al., 2014). In addition, consulting services offered by public organizations are also recommended, which advise companies particularly on the different areas of frugalization, but also support the search for suitable “frugal” partners.

In the emerging economies, awareness-building measures are required with regard to a more pronounced awareness of the negative external effects of UFI, such as environmental pollution and substances that are hazardous to health, and with regard to the understanding that AFI provide promising business opportunities. This is particularly important for the elimination of possible social damage, as described by Hossain (2021). Since these are due in particular to gaps in government regulation and its enforcement, these should be better developed. Competence-building measures should be the main focus in the emerging economies. In particular, the existing incentives to expand R&D capacity and the continuous improvement of conditions for production scalability should be further strengthened. In this context, international cooperation could also be interesting for emerging economies in order to be able to draw on the research know-how of multi-national companies from advanced economies.

CHAPTER THREE

Serving society at large. Operationalization and Evidence of (Advanced) Frugal Innovation in Industrialized Economies.

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Abstract

In existing works, frugal innovations are predominantly associated with emerging markets. Little is known about the development and diffusion of frugal innovations in industrialized economies or high-income countries. According to recent research, this can also be attributed to structural differences between emerging and industrialized economies. However, very little empirical research exists that examines the impact of such differences on frugal innovation. This paper develops initial steps towards assessing frugal attributes of existing products. In addition, it can be assumed that the application of certain frugal design principles inhibits attractiveness in certain markets due to the resulting lower level of amenities. However, frugality methods that rely more heavily on internal customization also exist. Accordingly, the possibility of using these methodologies also exists beyond serving the needs of the poor, fulfilling the needs of societies in general, including high-income population groups.

Acknowledgments

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3.1 Introduction

Research on frugal innovation (FI) started with a focus on emerging markets and products that serve the needs of the poor (e.g. George et al., 2012). Increasingly, however, researchers have become interested in the environmental benefits of FIs which may come as a side effect: FIs often result in substantial cost reductions through a focus on core functionalities and an optimized performance level, and these features in turn may reduce a product's material and energy consumption and prove environmentally beneficial. If these environmental benefits result from a rigorous engineering effort to cut excess material and energy use throughout a product's entire life cycle, the innovation is labeled an advanced frugal innovation (AFI) introduced and described in Rao 2017b). Other FIs, which achieve cost reduction through trial and error along with improvisation, are labeled unrefined frugal innovation (UFI) (Barnikol & Liefner, 2022).

Examples in the recent literature show that AFIs emerge from low-income countries as well as high-income countries, whereas UFI are usually discussed in the context of low-income economies or communities (Barnikol & Liefner, 2022; Wohlfart et al., 2016). These differences are presumably systemic: innovators in emerging economies have a profound knowledge of the needs of the poor, which becomes an asset in FI innovation processes, but the emerging economies' overall innovative capacity is limited. Innovators in industrialized economies have access to much stronger innovative capacity but lack a deep understanding of the living conditions of the globally poor. Their interest lies more in generating environmentally friendly products in order to respond to their customers' growing environmental concerns in Western markets. Overall, it can be assumed that FIs and especially those of the advanced type are able to generate growth that enables the inclusion of lower incomes in emerging and industrialized countries (Lim & Fujimoto, 2019).

As of today, however, empirical research that would substantiate these patterns and assumptions is lacking. The recent research on FIs has mainly focused on case studies of individual products and companies, and on reviewing conceptual considerations. One reason is the apparent lack of an operational approach to assess the degree of frugality of a product – in absolute terms or relative to a different product – with the help of a limited number of clearly defined characteristics. This paper puts forward such an operational approach and applies it to examining features of a mid-sized population

of novel products that have been generated in an industrialized economy. The focus on an industrialized economy was chosen for two reasons: firstly, company populations in industrialized economies tend to be more stratified in terms of innovative capacity and production costs than company populations in emerging economies (Beugelsdijk, 2007; Liefner & Losacker, 2020), making it easier to control for errors and misinterpretations. Secondly, while many FIs from emerging economies have been discussed in case study research, comparatively little attention has been paid to FIs from industrialized economies that serve the needs of high-income population groups in a global context.

This paper addresses the following two research questions: Firstly, how can the degree of frugality of products be measured empirically? Secondly, how common are frugal product features among product innovations in an industrialized economy setting?

This paper's approach is explorative in that it proposes one possible approach towards measuring frugality, thereby showing what might be learned from generating and analyzing quantitative data on FIs, acknowledging that other approaches will be developed in the future. Its empirical focus is on manufacturing companies' innovations in two German regions.

The remainder of this paper is structured as follows: Chapter 3.2 shows the general requirements for measuring FI and AFI, derived from the literature, and creates a measurement construct. In Chapter 3.3, this is operationalized and aggregated using data from a company survey, and the measurement model is interpreted. In Chapter 3.4, the different measurement dimensions are related to the frugal design principles and interpreted together with other influencing factors. Building on the findings from the previous Chapters and the existing literature, Chapter 3.5 hypothesizes and discusses possible development paths of AFIs. Chapter 3.6 provides a concluding summary and presents further requirements for action.

3.2 Dimensions of frugal innovations

A central challenge in measuring frugal innovation is how to deal with the many different definitions that exist in the literature. There are not only differences in detail, but also with regard to more general definitions in the classification of new products as frugal. On the one hand, this makes it necessary to continuously structure the young research field, which is indicated by a high number of review papers. On the other

hand, it makes it more difficult for the research field to progress due to the lack of a single accepted definition. Taking into account the relevant literature, a simpler perspective on frugal innovation in general and AFI in particular can reduce the diversity of definitions, contexts and characteristics, enabling the development of a construct that allows the application of quantitative methods in the research field.

3.2.1 Complexity and difference of definitions

The definition of FI is still in an evolutionary process and under constant development. Product characteristics, such as the use of simpler and cheaper materials, as well as limited functions that are the result of strong resource constraints and extreme cost advantages (Zeschky et al., 2011) form a predominantly consistent part of the definitions. Weyrauch and Herstatt (2016), who develop one of the most widely used definitions of frugal innovation, also define FI similarly based on the concentration on core functionalities, optimized performance level and substantial cost reduction. Although this definition provides a good framework for qualitative research, it hinders the application of quantitative methods, as the degree of uncertainty is too high (Brem, 2017).

In addition, the perspective on the benefits of frugal innovations in particular has changed. In the beginning, this was primarily attributed to the so-called Bottom of the Pyramid (BoP) (Brem & Wolfram, 2014; Kroll & Gabriel, 2020; Ray & Ray, 2011). Frugal design principles such as the limitation and reduction of functions as well as optimized coordination of product components serve in this context as enablers of lower costs. This in turn enables the consumption of financially weaker population groups and is strongly related to the emerging economies (Prahalad, 2012; Zeschky, Winterhalter, et al., 2014). In recent years, many Articles have also classified the aspect of sustainability as an essential component of frugal innovations (e.g. Barnikol & Liefner, 2022; Basu et al., 2013; Hossain, 2021b; Rao, 2014). Others claim that sustainability is not a necessity, but rather a potential side benefit (e.g. Albert, 2019) which can strongly differ between different actors (e.g. De Marchi et al., 2022). Based on the work of Rao (2013, 2017a, 2019), Barnikol & Liefner (2022) argue that the environmental and social perspectives cannot be separated. Accordingly, a cost reduction can also be the conscious or unconscious result of reducing or replacing environmentally friendly but expensive product components. The costs of the product are thereby only shifted and not reduced. Ensuring this, on the other hand, requires

extensive knowledge on the part of the developers and, according to Rao (2017b), is made possible by a sophisticated development process and frugal engineering (e.g. Rao, 2022), which requires, among other things, the use of modern materials and production techniques. This form of frugal innovation is called advanced frugal innovation (Barnikol & Liefner, 2022; Rao, 2017c, 2017b).

3.2.2 Dimensions of frugal innovation

Despite the different and partly contradictory characteristics of frugal innovations depending on the authors and disciplines, a commonality can be identified considering the dimensions that affect frugal innovations. With regard to the measurement of frugal innovation, a distinction can be made between input, output and outcome (Table 4). A similar approach was used by Kroll et al. (2016), who defined the overarching commonalities of frugal innovations on the basis of the product, process and context dimensions. Compared to Kroll et al. (2016), however, the respective characteristics, which are referred to here as linear dimensions, are deliberately kept more variable and do not claim to be exhaustive.

Table 4: Dimensions of frugal innovation

Development process/design (input)	Product characteristics (output)	Environmental and aggregated societal impact (outcome)
- Design adaptions towards outcome - Concentration on core functionalities - Optimized performance level - Simple design instead of opulent design - Scientific principles - (…)	- Reusable/recyclable - (Low) Energy consumption - Low material consumption - Use of renewable energy - Reuse of materials - Economical/efficient in use - (…)	- Environmental sustainability - Socio-economic sustainability: ”serving the needs of the poor” - Inclusive consumption and growth - (…)

As explained before, frugal innovations, regardless of different specifics such as AFI, are in the context of a certain purpose. The purpose that covers the level of the outcome includes the impact of the product (Table 4). In the literature, different aspects are mentioned, mainly expressed by positive effects for the environment through increased sustainability and for society through the provision of affordable products (e.g. Barnikol & Liefner, 2022; De Marchi, Pineda-Escobar, et al., 2022; Liefner et al., 2020; Rao, 2013). Depending on the product, however, the actual effect is very

comprehensive and requires considerable research and analysis. Accordingly, this latent dimension is difficult to operationalize and rather serves as a target.

Since the outcome and the actual effects of a product are difficult to capture even in qualitative studies, the consideration of the final product properties (output) represents one way to capture the outcome. Accordingly, this is to be considered as a proxy of the outcome and as a strong simplification. Corresponding variables can include, for example, the cost of the product, which can represent affordability in a social context. At the same time, the use of reusable and renewable resources and components as a product characteristic can be considered as an indicator of sustainability (Rao, 2013, 2021). However, it is crucial here that no fixed package of variables can be created. Accordingly, it is essential that the output variables used as proxies for outcome are adjusted between individual studies, taking into account the nature of products and markets. For example, individual variables such as the type of raw materials used are more meaningful in the context of manufacturing than in services.

Finally, the input includes the frugal design principles or the development process and the design that are applied to achieve the output, and thus indirectly the outcome. Accordingly, frugal design principles are the enablers - the path to frugal and especially advanced frugal innovation. These are also not limited to individual approaches, such as limiting or reducing functions (Weyrauch & Herstatt, 2016; Zeschky et al., 2011), creativity techniques (Brem et al., 2020), or the use of modern production techniques and processes (Rao, 2017c, 2019). In accordance with the diversity and complexity of different product groups with diversified customer groups and environmental influences such as regulations and know-how, it is to be expected that the same input factors have a different impact in different development processes for different products. The limitation to individual methodologies, as for example in the definition by Weyrauch and Herstatt (2016), would strongly limit the potential of the entire research field by excluding other and new frugality techniques. In addition, the consideration of a variety of frugality techniques offers the possibility of comparison as well as the modeling of favorable combinations of different input factors.

3.2.3 (Advanced) Frugal innovation as a construct

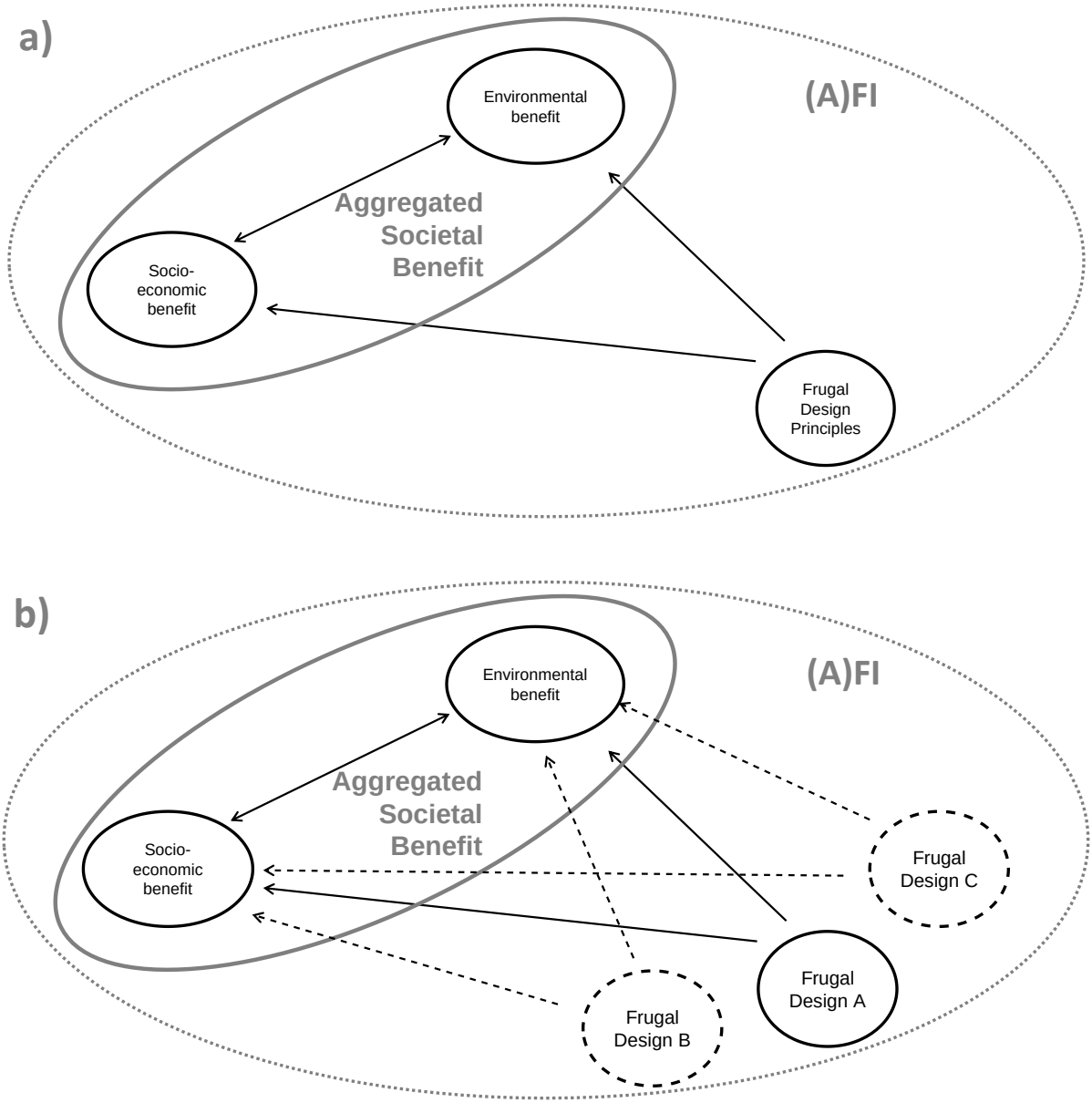
The structured perspective and the dimensions of frugal innovations derived from it enable the development of a theoretical construct that allows the quantitative measurement of frugal innovation (Figure 6). Furthermore, this measurement construct

can be applied to all frugal innovations, regardless of product type and industry, and to both the advanced and unrefined type. While the nature of innovativeness is debated in the literature (e.g. Lim and Fujimoto, 2019), in the proposed construct, innovativeness is defined by the new socio-economic and environmental benefits to society.

Basically, the construct consists of two levels that essentially cover the properties of the input, output and outcome dimensions described in the previous Chapters. The levels represent the aggregated societal benefit on the one hand and the design on the other (see Figure 6). The aggregated societal benefit represents the relationship between the socio-economic and environmental benefit of a product. The aggregation of these two factors should be in a positive balance to ensure that there is an aggregated societal benefit and that there is no shift of monetary costs to the detriment of sustainability (see Barnikol & Liefner, 2022). If this is the case, it shows the innovative character of the product from a new-to-market (OECD & Eurostat, 2018) perspective. If the socio-economic benefit (cost reductions) comes at the expense of environmental benefit, e.g. through the use of cheap but hazardous material, a product's total benefit may be reduced. And conversely, some slight improvement in terms of energy use in combination with a sharp cost increase would also be unwelcome. On the other hand, the balance of the aggregated societal benefit also ensures that sustainable products are affordable products and that environmental friendliness is not accompanied by higher costs, as is the case with many products due to the lack of comprehensive consideration of environmental costs for standard products. The two characteristics of socio-economic and environmental benefit are latent, which requires an individual selection of suitable variables depending on products and industries to adequately reflect the effect (see Chapter 3.2.2). The design level includes the input that enables the aggregated societal benefit and can be subsumed under the umbrella term of frugal design principles (FDP). This includes the complete variation of existing and as yet unknown methods that follow the classic principle "more with less" (Prabhu, 2017) and minimization of resources (Sarkar & Mateus, 2022). It includes both technological and architectural adaptations, whereby novelty is not a necessary but helpful criterion for success in order to generate a better cost-benefit ratio (Lim & Fujimoto, 2019). In this context, multi-pronged engineering processes such as those proposed by the "Factor of Frugality" (Rao, 2017c, 2018, 2019), but also individual measures such as the reduction of functions (Weyrauch &

Herstatt, 2016; Zeschky et al., 2011) and approaches such as brainstorming (Brem et al., 2020), can be compared in terms of their effectiveness and possible combinations (Figure 6 a), b)). These frugal design principles are the enablers of aggregated societal benefits within the framework of frugal innovation.

Figure 6: The construct of (advanced) frugal innovation



In this construct, frugal innovation in general is defined as the relationship between frugal design principles and the resulting aggregated societal benefits in terms of environmental and socio-economic benefit. Accordingly, the cause-effect relationship can be mapped in different contexts. This bipartite perspective is crucial and offers a significant advantage in measuring frugal innovation compared to existing analyses in

which frugal innovation is predominantly represented by a single parameter (see AlMulhim, 2021; Altgilbers et al., 2020; Dost et al., 2019; Dwiedienawati et al., 2021; Iqbal et al., 2020, 2021; Kronemeyer et al., 2020, 2021; Ploeg et al., 2020; Rossetto et al., 2017; Santos et al., 2020). Representing frugal innovation in a single variable entails a loss of information that assumes causality between the attributes without proving it. Accordingly, the definitional logic that can be considered useful in the context of case studies is not easily transferable to quantitative studies and underlines the need for a different approach in this context, as this construct provides. This construct widens the field further and offers the opportunity to exploit the potential behind the logic of (A)FI to a greater extent.

3.3 Methodology

In order to empirically capture FI in industrialized economies, a company survey was conducted in the first half of 2022. In addition to general questions about the company, the survey used an object approach, asking questions about the company's top-selling product, its characteristics, and external influences on its product characteristics in comparison to the most important competing products, indicating differences on a 7-point Likert scale. The survey is also suitable to test the theoretically derived measurement model and to discuss the existence of FI in industrialized economies. However, it is necessary to consider the framework and content of the survey to be able to classify the results. The relevant parts of the used questionnaire are deposited in Appendix A.

3.3.1 Survey and operationalization

The survey was conducted in the German states of Lower Saxony and Hesse: in Lower Saxony from 23 May to 19 June 2022 and in Hesse from 21 June to 17 July 2022, which corresponds to a survey period of 4 weeks. All information relates to the product with the highest sales and, at company level, to data for the most recently completed business year. The survey included companies from the manufacturing sector only. An invitation to participate in the survey was sent out by email and returning questionnaires were collected online. In both federal states, the invitation was sent by an external partner who addressed the companies directly via an internal distribution list. This was the Association of Lower Saxony Business Associations in Lower Saxony and RKW Hessen in cooperation with local chambers of commerce and Hessen Agentur in Hesse. The partners usually approached CEOs in each company. There

was no way to ascertain, however, whether CEOs may have delegated the task of filling in the questionnaire internally. In total, 96 companies (2.9% of the basic population) participated in the survey. For the purpose of this work, 86 questionnaires can be used, which corresponds to 2.6% of the basic population (see Table 5). A self-selection bias cannot be excluded, although general characteristics of the sample and the population do not differ. The questionnaire was rather long and demanding. This, along with operative stress on the part of companies, may have limited the willingness to participate: both survey periods fell within the first months of the war in Ukraine and were still affected by the Covid-19 pandemic.

Table 5: Survey participation and response rate

	Participation	Usable	Population
Lower Saxony	79 (4.1%)	71 (3.7%)	1931*
Hesse	17 (1.3%)	15 (1.1%)	1359*
Total	96 (2.9%)	86 (2.6%)	3293

**preliminary official data from July 2022 (Destatis, 2022)*

In this context, it is necessary to take into account the different weighting of the regions in terms of both the basic willingness to participate and the evaluability of the questionnaires. Accordingly, the manufacturing sector in Lower Saxony is weighted significantly higher than that in Hesse, but this has little impact on the analyses conducted in this Article. Due to the small share as well as the focus on the product with the highest sales, the representativeness of the data is limited. Nevertheless, the data is sufficient to offer initial conclusions and exploratory insights into the meaningfulness of the measurement construct as well as the existence of FI in industrialized economies.

The selection of questions for the survey of the product characteristics of FI was made on the basis of the relevant literature. In particular, properties and design for the development of advanced frugal innovation (Barnikol & Liefner, 2022; Rao, 2017b, 2017a, 2018, 2019) were considered for this purpose. Especially decisive for this were the consideration and adaptation to the manufacturing industry as well as the selection of suitable variables from the three areas of environmental and socio-economic benefit along with design (see Table 6). In the questionnaire, the participants were asked to assess the characteristics (much lower to much higher) of their top-selling product in relation to the average product of the competition on a 7-point Likert scale. The aim

here was to determine how these characteristics compare to the market and whether they can represent an actual aggregated societal benefit. Cognitive pretests were carried out followed by pretests of the questionnaire with satisfactory results, showing a common understanding of the questions. Department heads, founders, as well as program and sales managers from different levels were included. In addition, the questionnaire was discussed with staff from business development, advocacy, think tanks and a ministry.

Table 6: Variables for the construct of AFI

Factor	Code	Variable
Environmental benefit	EFPU	Environmental friendliness of production and use (type of energy, circular economy etc.)
	SMPU	Use of sustainable materials in production and use
	Ao4R	Application of 4R (reduce, reuse, recycle, rethink)
Socio-economic benefit	SePr	Selling price
	MOCU	Maintaining and operating cost in use
Design	CoCF	Concentration on core functionalities
	UoSC	Use of standard components not tailored to the product
	EESP	Effective and efficient solutions for the purpose of use
	UoAM	Use of advanced materials
	UoAT	Use of advanced technologies

Variables are selected regarding their fit with AFI mainly based on the following literature Albert, 2019; Barnikol & Liefner, 2022; Rao, 2017a, 2017b, 2017c, 2018, 2019; Weyrauch & Herstatt, 2016; Winkler et al., 2020

3.3.2 Aggregation of advanced frugal innovation dimensions

The measurement logic presented in Chapter 3.2.3 suggests a reflective measurement model for the aggregation. In the case of the present data and the industries considered, the factors shown in Table 6 can be aggregated with the help of the variables mentioned. The meaningfulness of this theoretically based variable composition was proven by means of a confirmatory factor analysis. The factors environmental benefit and socio-economic benefit were determined. These two variables serve as the basis for the calculation of the aggregated societal benefit. Design as a separate factor is not considered, since aggregation could result in a loss of information. In the future, there is a possibility of bundling individual design packages whose components work with each other, but at this stage more research is needed. The effect of the designs on the factors is discussed separately in Chapter 3.4.

$$(1)\ Socio-Economic\ Benefit = \overline{SEB} = \frac{-1}{n} * \sum_{i=1}^{n} SEB_i = \frac{-SePr - MOCU}{2}$$

$$(2)\ Environmental\ Benefit = \overline{EB} = \frac{1}{n} * \sum_{i=1}^{n} EB_i = \frac{EFPU + SMPU + Ao4R}{3}$$

$$(3)\ Aggregated\ Societal\ Benefit = \overline{ASB} = \frac{\overline{EB} + \overline{SEB}}{2}$$

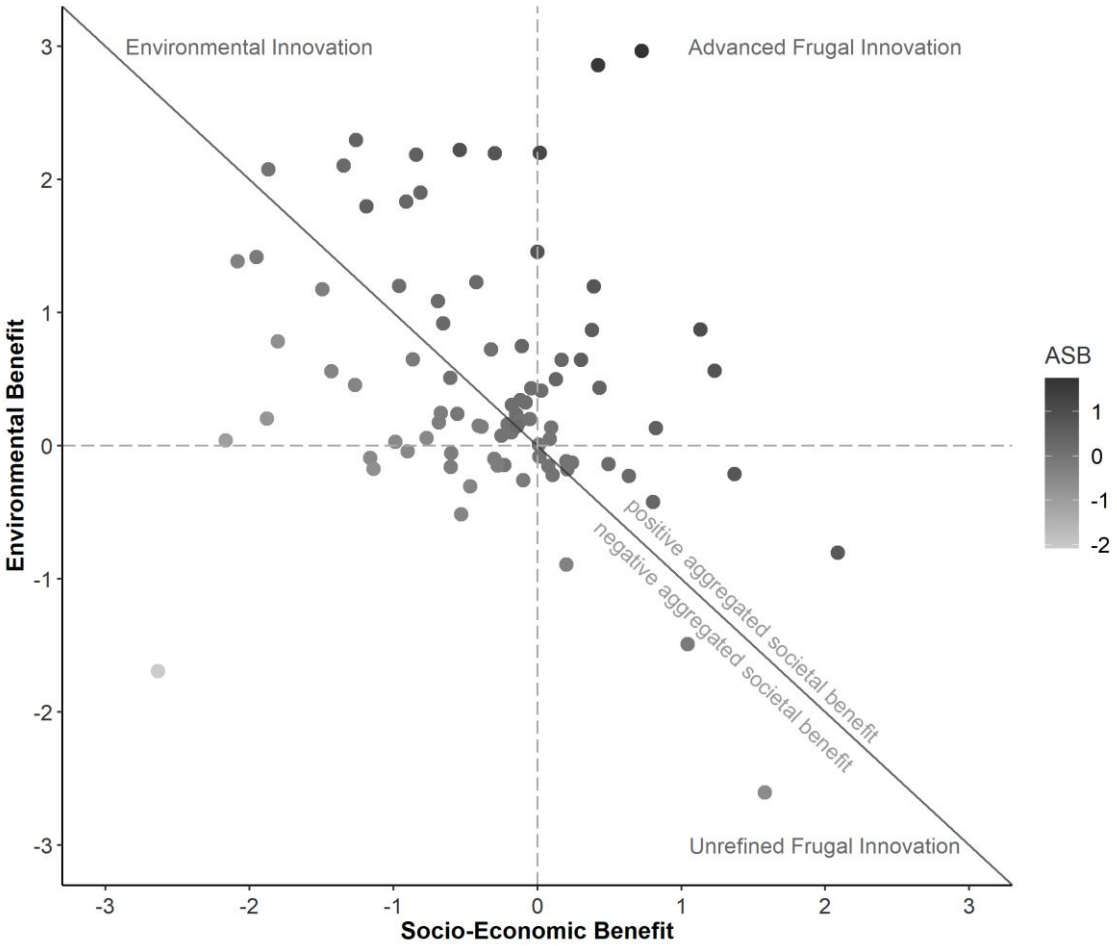
In this case, simple aggregation based on means is obvious. The distribution of the calculated variables as well as the used indicators can be found in Appendix 1. Another possibility would be the aggregation based on the factor loadings in different ways, but these can differ greatly between samples, which is why the use of simple averages is more stable (DiStefano et al., 2009). Accordingly, the factors socio-economic and environmental as well as aggregated societal benefit are aggregated according to the formulas (1), (2) and (3), while socio-economic and environmental benefit are calculated from the variables listed in Table 6 with the expressions -3 to 3. These aggregates also form the basis for calculating aggregated societal benefits. Both aggregates are included in the evaluation on an equal weighting basis. In addition, the question wording is also taken into account, which in this case links positive values to a stronger expression of a product characteristic. In the case of cost-related variables, this is crucial in order to make the interpretation of socio-economic benefits more intuitive and to avoid false conclusions. For this purpose, the cost-related variables in the calculation were given a negative sign, which means that a higher socio-economic benefit is associated with a lower price (see equation (1)).

The combination of these aggregates provides a good picture of the direction of impact and information value of the aggregated societal benefit. This is shown in Figure 7, which puts all products in one figure according to their attributes, thus combining the environmental and socio-economic perspectives. The color gradient represent the strength of the aggregated societal benefit. A similar scheme can already be found in Kroll et al. (2016), which compares costs and ecological footprint. In Figure 7, the products in the upper right half have a general positive aggregated societal benefit, while the products in the lower left half have a general negative one. However, this alone does not determine whether these products are AFIs, but rather defines them as candidates that can be classified as AFIs in combination with frugal design principles.

According to the mathematical and theoretical logic defined in advance, the two variables of environmental and socio-economic benefit do not both have to be positive, but only need to have an overall positive effect. Accordingly, an AFI candidate can have a negative environmental benefit but can more than compensate for it with a correspondingly higher socio-economic benefit. In contrast, an AFI candidate can have a negative economic effect if the environmental effect is correspondingly higher in absolute terms. The resulting balance links the social and environmental impact of product development with technological progress. However, Figure 7 also shows that the majority of cases of AFI candidates have both a positive socio-economic and environmental benefit. In this context, it can be observed that the distribution is concentrated closer to the origin, and that there are only a few cases with a strong environmental benefit and none with a strong socio-economic benefit. Accordingly, there are no cases with a strong environmental and socio-economic benefit. This indicates that the common progress of both the environmental and socio-economic benefit are associated with a considerable challenge.

In addition to narrowing down potential advanced frugal innovation on the basis of positive aggregated societal benefits, two further forms of innovation can be classified in the context of advanced frugal innovation based on Figure 7. Firstly, unrefined frugal innovation can be narrowed down in the fourth quadrant (see Barnikol & Liefner, 2022). These have a positive socio-economic effect but are unable to combine this with a neutral or positive environmental benefit in comparison to the market. The reason for this could be regulatory-institutional weaknesses that allow costs to be shifted from the monetary to the non-monetary realm, for example by using cheap but environmentally unfriendly materials. In contrast, environmental innovations can be located in the first and second quadrants. The standard of definition here is only the positive environmental benefit regardless of the costs. Accordingly, the intersection of unrefined frugal innovation, environmental innovation and advanced frugal innovation can be seen. In contrast to the first two, the consideration of both socio-economic and environmental effects is relevant for AFI, indicated by a positive aggregated societal benefit.

Figure 7: Aggregated societal benefit of products from manufacturing industries



Representation was created using the jittered method to better represent the distribution.

3.4 Empirical results

The theoretical derivation and operationalization of the measurement construct have shown the complexity of advanced frugal innovation and illustrated how the three benefits can be interpreted. Regarding the diffusion of advanced frugal innovation, two perspectives are relevant. First of all, the connection of the frugal design principles with the aggregated societal, environmental and socio-economic benefits has to be proven. It has to be examined whether existing rationales from emerging economies are also valid in industrialized economies and whether the aggregated societal benefit can be traced back to them (see Chapter 3.4.1). The overview in Figure 7 shows, that the distribution of the product related variables tends to be oriented along the equilibrium of a neutral aggregated societal benefit with very few products reaching far into the AFI

field. There is hence only very limited evidence of a dual positive environmental and socio-economic benefit. Accordingly, it is to be expected that the application of frugal design principles does not have a similar influence on both benefits and does not represent an automatism. On the other hand, external factors can also have an influence on the benefit dimensions. For this purpose, the company-related data is linked with the product-related data in Chapter 3.4.2 (see Figure 8). In addition, industry-related influences were also examined, but due to the small number of cases in individual industries, no clear differences were found. The results have been appended for completeness (see Appendix 4) but not discussed in the text.

3.4.1 Influence of frugal design principles

From a theoretical perspective, it can be assumed that the selected variables predominantly have a positive effect on the aggregated societal benefit and the socio-economic or environmental benefit. However, these relationships have not been tested in quantitative studies and their assumptions are mainly based on theoretical considerations of the current literature, especially various case studies. It should be noted that these design principles have been observed mainly in the context of emerging economies, and many of them only to reduce costs. The results of these data show a rather differentiated picture of both the effectiveness and the direction of impact in the context of aggregated societal, socio-economic and environmental benefit. Detailed information about the distribution of the variables can be found in Appendix 2.

Of particular significance is the relationship between the socio-economic and environmental benefits. The negative correlation of the two benefit dimensions (see Table 7), which has already been pointed out and can also be observed visually in Figure 7, also offers an explanation for the observation that only one of the design principles considered has a significant influence on the aggregated societal benefit. Correspondingly, the concurrence of socio-economic and environmental benefit is not automatic, even with the application of specific methods, and is confirmed by the negative correlation (see Table 7). This justifies the assumption that a targeted deviation of different designs and practices is necessary to achieve both the environmental and socio-economic benefit and to maximize the aggregated societal benefit. In addition, support for the hypothesis that cost reduction in the development of frugal innovation can also be achieved through the use of environmentally harmful

resources and technologies can be seen in this context (Barnikol & Liefner, 2022; Hossain, 2021a). Moreover, the existence of this relationship shows that there are still institutional weaknesses in terms of regulations that allow such cost shifting.

Table 7: Interrelationship between frugal design principles used and product benefits

	ASB	**SEB**	**EB**	CoCF	UoSC	EESP	UoAM	UoAT
ASB	*1*							
SEB	***0.53****	*1*						
EB	***0.57****	***-0.26****	*1*					
COCF	*-0.13*	***-0.35****	*0.19**	*1*				
UoSC	***-0.34****	***-0.25****	*-0.11*	*0.16*	*1*			
EESP	*-0.15*	***-0.34****	*0.12*	***0.57****	***0.40****	*1*		
UoAM	*0.16*	***-0.28****	***0.55****	*0.20**	*0.09*	*0.19**	*1*	
UoAT	*0.9*	***-0.29****	***0.36****	***0.28****	*0.07*	***0.43****	***0.58****	*1*

*n=86,*** <0.01, **<0.05 *<0.10 according to Spearman rank correlation*

In general, our data does not show a clear direct correlation between the frugal design principles and a higher aggregated societal benefit. In addition to the socio-economic and environmental benefit, which have a correlation with the aggregated societal benefit based on a mathematical logic, only the use of standard components is related to the aggregated societal benefit. This is negative and exists presumably for the same reasons as in connection with the socio-economic effect (see Table 7). A basic principle for the development of frugal innovations is the adjustment component composition. An attempt is made to optimize the performance level of the products by selecting suitable components considering the user and product-related performance (Winkler et al., 2020) in order to avoid over-engineering and hence higher costs and resource consumption. In this connection, the use of adapted components which are tailored to the product can favor a better price performance ratio and optimized resource consumption in comparison with competing products. Conversely, a higher use of standard components leads to a negative effect on the socio-economic benefit, which is confirmed by these data. The stronger correlation with the aggregated societal benefit is statistically explained by the negative correlation with the environmental benefit, which is not significant in this data set, but is implied and theoretically substantiated.

It is important to note that the FDPs, in contrast to the aggregated societal benefit, have an effect on the socio-economic and environmental benefit, but seem to have unequal effects on different benefit dimensions. The relationship between the frugal

design principles and the socio-economic and environmental benefit shows the aforementioned opposition of the variables. Besides the previously mentioned relationship of the use of standard components, all other variables point to a negative relationship with the socio-economic benefit. In particular, the use of advanced materials and technologies has a positive environmental effect, but is expensive and therefore seems to have a negative impact on the socio-economic benefit. In contrast, the negative correlation of the variables “concentration on core function” and “effective and efficient solution for the purpose of use” (see Table 7) contradicts the existing literature (e.g. Weyrauch & Herstatt, 2016; Winkler et al., 2020). However, the literature mainly refers to private end customers as consumers of FI (e.g. Costa et al., 2021; Prahalad, 2012; Ray & Ray, 2011), Barnikol and Liefner (2022) point out that the consideration of pre-products, bought-in technologies and machines are also relevant for the generation of AFIs, especially in the case of complex products. 9 % of the products considered here are sold to business customers, while only 9 % are supplied to private end customers. A small proportion of companies serve both private and business customers. Accordingly, it can be assumed that these products are predominantly intermediate products or are used as part of the customers' production process. The data show that the behavior of companies in the development process is expressed differently. For example, the correlation matrix provides evidence for the assumption that a focus on core functions for the companies also means an improved performance of these same core functions. Accordingly, the current performance is not maintained but rather optimized with regard to the maximum possible in order to ensure the best possible performance. This is also indicated by the fact that both the focus on core function and effective and efficient solutions for the purpose of use are associated with a higher use of advanced materials and technologies. This is supported by the positive correlation of the focus on core functions with environmental benefit. This illustrates that it is only a technological exhaustion of functions that reduces the environmental friendliness and increases costs.

Overall, the influence of the design approaches and techniques mentioned shows the complexity of developing AFI in industrialized economies. The data underlines that the different characteristics of aggregated societal benefit in terms of socio-economic and environmental benefit have to be taken into account. This is particularly relevant when examining the impact of individual design principles and their combination. Accordingly, the three benefit variables should always be understood in an

interdependent context when evaluating methods, practices and procedures. With the data and variables used, no simultaneous positive effect for both the environmental and socio-economic benefit could be demonstrated by a single approach. Therefore, the application of single design approaches only does not seem to be a sufficient condition to increase the benefit dimensions. However, this does not contradict more comprehensive approaches such as the FoF, which examines the use of individual design measures (Rao, 2017c, 2017b, 2019, 2022) and is difficult to verify with the data used in this Article. As explained earlier (Chapter 503.2.3), it may be useful to test individual packages of frugal design principles and their impact on the benefit dimensions separately in further research.

3.4.2 Company-related influence on aggregated societal benefit

The aggregated societal benefit seems to be influenced by company-related factors in particular. Figure 8 shows trends indicating that both the size of the company, in terms of sales and number of employees, and its export orientation have an influence on the characteristics of the benefit dimensions. Accordingly, this provides initial indications of external factors influencing these dimensions. In addition, detailed information about the distribution of the variables can be found in Appendix 3.

In general, there is a slight tendency for the aggregated societal benefit of the top-selling product to be higher at larger companies. This can be observed on the basis of these data in terms of both the number of employees and sales (see Figure 8). The reasons for this can be manifold. It is conceivable that larger companies receive greater social attention and are therefore more likely to be forced to act in conformity with society as a whole in order to maintain a positive brand image and thus be able to sell their own products better and keep their attractiveness high in terms of recruiting new employees (Lemmink et al., 2003). In detail, however, the contrasting characteristics of socio-economic and environmental benefit are also apparent, which maintains the hypothesis of an underlying shift in costs or inadequate monetary coverage of environmental costs (see Chapter 3.4.1). An alternative or supplementary explanation could also be the label sustainability as a sales argument (see Conrad, 2005), whereby the actual added value is sometimes overemphasized in monetary terms or expensive certifications are given weight. An example of this is organic certification and products that fall into the category of sustainable luxury (Athwal et al., 2019; Wohlfart et al., 2021).

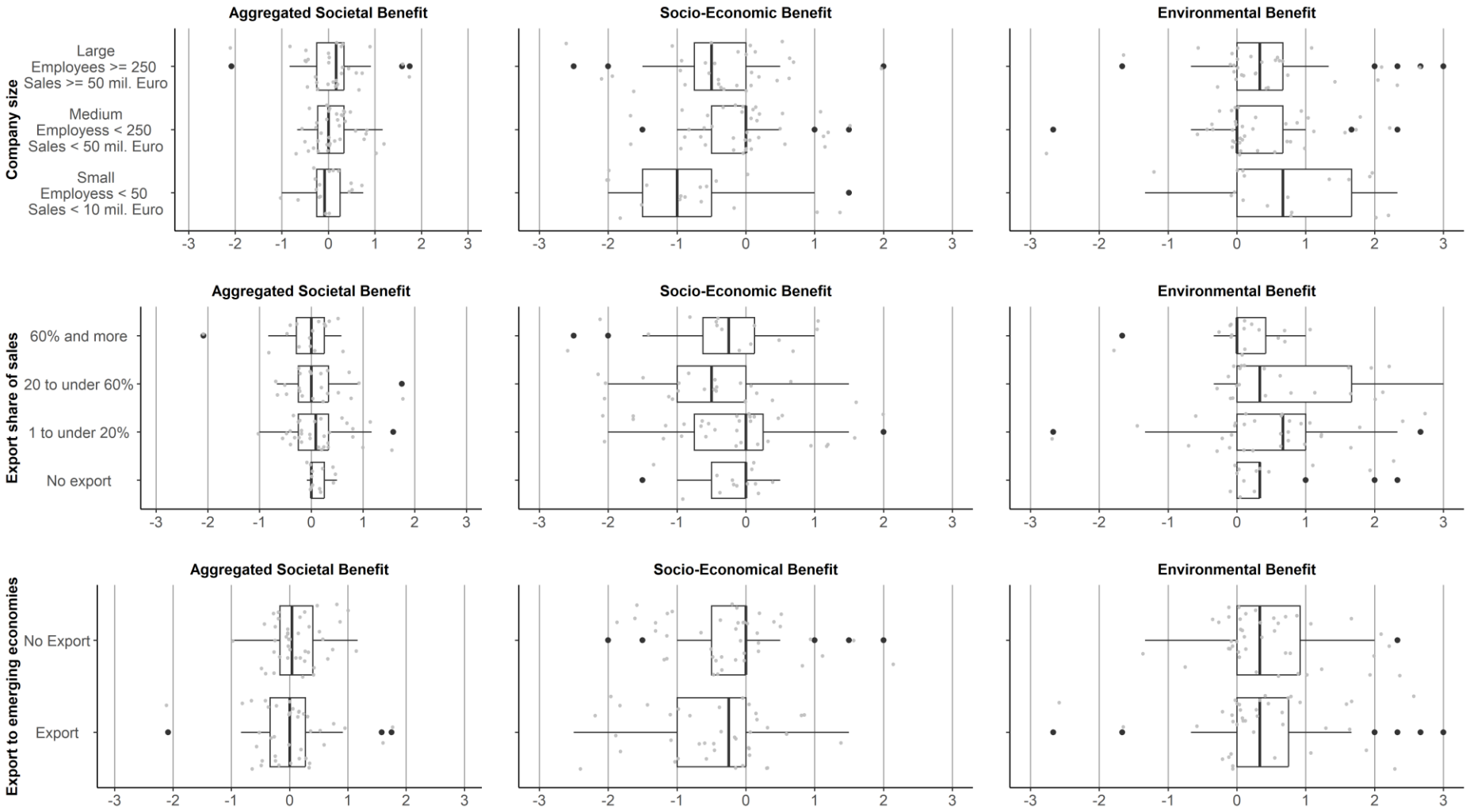
Taking the size classes into account, further patterns can be identified. In particular, structural differences emerge between small, medium-sized and large companies. In this data set, small companies seem to be more inclined toward extremes in terms of socio-economic and environmental benefits. Even though the spread is significantly larger than in the case of medium-sized companies, the median in the two benefit dimensions stands out clearly. Accordingly, the top-selling products of small companies represent both more sustainable and more cost-intensive products in competition. The significant majority of these companies are older than 10 years, which is why it can be assumed that these are specialized rather than young companies that serve a niche, for example. In this niche, there could be demand for precisely these sustainable product features that are not yet established at a higher level (see Barnikol & Liefner, 2022). There are indications that small companies in particular are more environmentally friendly in the processing and construction of products (Dzeraviaha, 2022), and that consumers are willing to pay more money for these products (Conrad, 2005). In addition, the data show higher maintenance and operating costs given the same durability and robustness of small company products. Due to their low sales, which are below 10 million euros, economies of scale tend to be exploited to a lesser extent than in companies with higher sales. Precise production techniques are also more difficult to apply there due to unadapted machines. Accordingly, the median aggregated societal benefit for smaller companies in the present data set is negative.

Large companies in the data set show a similar pattern, albeit significantly weaker. They, too, show a contrasting trend in environmental and socio-economic benefit. In contrast to the small companies, the median is lower in both dimensions and the dispersion of the group is also lower. There is evidence in the literature that larger companies are sustainable. One reason is that these companies are more in the focus of society and therefore also have to consider its interests more transparently, thus also being able to present their social legitimacy (Schreck & Raithel, 2018). With a positive brand image, companies can more easily recruit talent and charge higher prices for their products (Lemmink et al., 2003; Nickerson et al., 2022). At the same time, size also offers the advantage of being able to deal more efficiently with resources and the energy used, for example through recycling, such as the use of waste heat, as well as generating economies of scale and resource efficiency (Dzeraviaha, 2022; Triguero et al., 2022).

Medium-sized companies in the data set have the smallest socio-economic and environmental benefits. It can be seen that they are distributed close to the average of the competition and that the median of both dimensions lies at this level. Here, the same tendency of a negative socio-economic effect as well as a positive environmental effect can be observed, which, however, turns out to be significantly smaller. These companies seem to represent the middle of the market with pressure from adaptable young as well as large dominant companies. It can be assumed that these companies are too large to serve a specialized niche in which, for example, frugal design principles are accepted. At the same time, these companies may still be too small to set their own standards and too unknown to benefit from an image-building sustainability reputation.

Another determinant that seems to have an influence on the benefit dimensions is export orientation and competition in different markets. A slight tendency can also be observed in the relation between the export share of the product with the highest sales and the aggregated societal benefit. In the data set, the mean value of the aggregated societal benefit of products that are not exported decreases for products that are 60% exported and more. A clear trend can be seen particularly in the context of the environmental benefit. On average, this is significantly higher for products that are between 1 and 20% exported than for the remaining exported products. The same is true for the socio-economic benefit. The mean negative value is significantly higher for products that are 20% exported than for products less than 20% exported or not exported at all.

Figure 8: Company related moderators of the product benefit dimensions



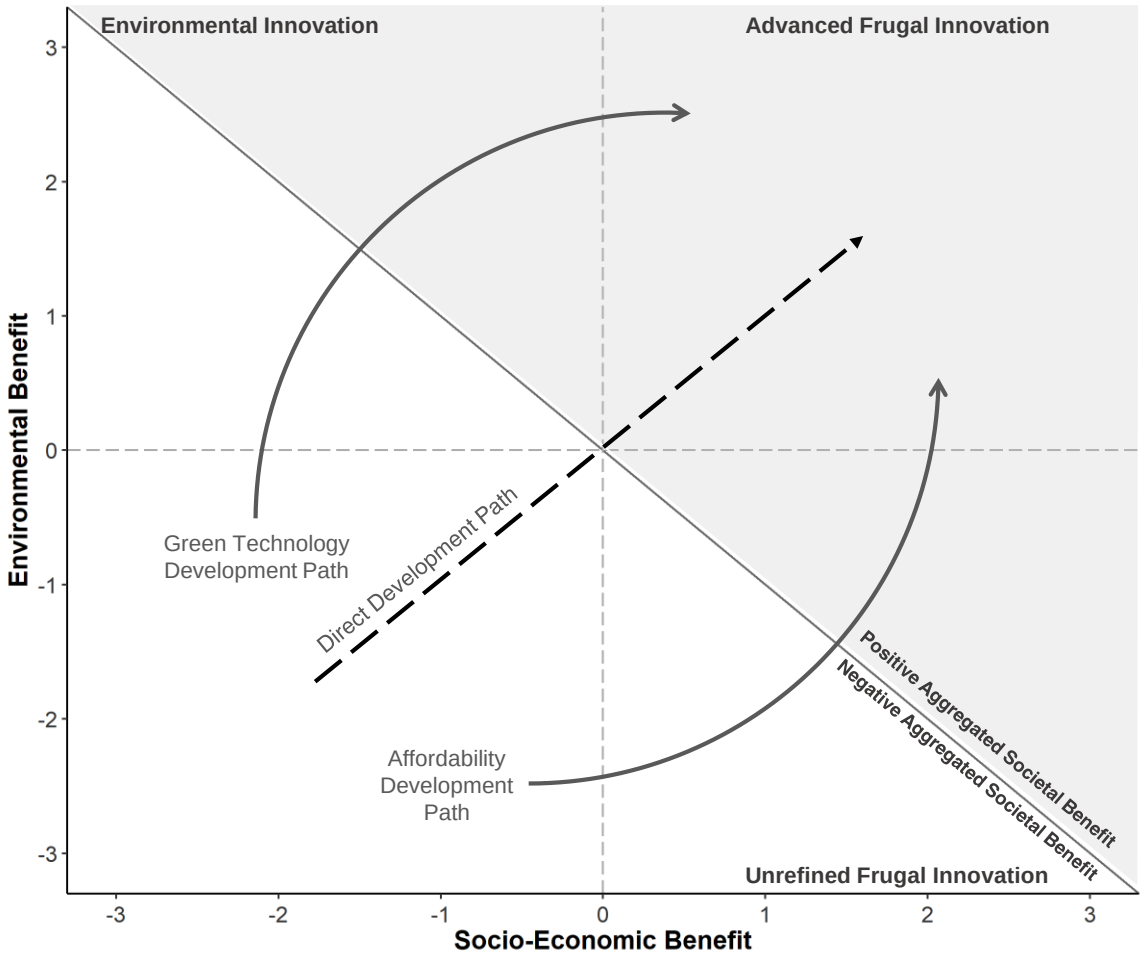
This is remarkable for two reasons that are not mutually exclusive. Firstly, a measuring effect must be taken into account in this context. Since the respondents were asked to compare their top-selling product with the competition, the competition multiplies depending on whether the company is only present in one national market or participates in international competition in different markets. Accordingly, the variety of products changes and regionally specific needs become less important in order to be able to represent a common denominator. Secondly, in the case of the present data, this leads to two contradictory interpretations that cannot be conclusively validated with the available information. On the one hand, German companies incorporate regional or national environmental claims into their products, which are not in great demand internationally and therefore have a more positive environmental benefit. On the other hand, these companies could also be predominantly active in countries where higher environmental demands exist, where these products have a unique selling proposition and are exported there for this very reason. Overall, the socio-economic benefit tends to be negative for the exporting companies. From an international perspective, with Germany as a high-wage country (ILO, 2020), this is understandable. The literature shows that Western companies also export frugal products to emerging markets, but often remain in the premium segment despite cost reductions (Barnikol & Liefner, 2022; Zeschky et al., 2011). This is reflected in the distribution of the socio-economic benefit of the products exported to emerging markets, which, in contrast to the non-exported products, show a predominantly negative effect. It is remarkable that the environmental benefit of the products exported to emerging markets and those not exported seems to be similar.

3.5 Discussion

Based on the findings from Chapter 3.3 and 3.4, mechanisms can be derived that enable the formation of a hypothesis about the market-related path of the origin of AFIs. The comparison of environmental and socio-economic benefits, the basic dimensions of aggregate benefits (see Figure 7), shows that the two are not usually found to go hand-in-hand. Instead, it can be deduced that the development of advanced frugal innovation and the consideration of both basic positions is associated with considerable challenges. This is not only shown by the negative correlation between environmental and socio-economic benefit, but also by the opposite effect of the selected frugal design principles considered (see Table 7). Based on the

explorative findings and supplemented by the existing literature, the hypothesis can be formulated that the development of AFI essentially follows two paths which are different from a potentially challenging straight path (see Figure 9).

Figure 9: Hypothetical market-related development paths of AFI



The first path is essentially based on economies of scale (affordability development path). The initial focus here is on the socio-economic benefit. By scaling a product, it is possible to reduce its unit costs and thus also create the possibility of a competitive price reduction. This corresponds to the development path of a typical frugal innovation, which is characterized by a shift in the cost-performance frontier, thus offering qualitative equivalent or even higher-quality products at lower prices in the market (Lim & Fujimoto, 2019). In the rationale of Figure 9, this shifts the position of the product in the competition to the right and increases the socio-economic benefit as well as the aggregated societal benefit. The environmental benefit either remains unaffected or increases slightly through more efficient use of energy, resources and others. With increasing scale and corresponding competitiveness, there is the

possibility to use additional cost advantages to increase the environmental benefit. This can be achieved through gradual adaptation in design, use of environmentally friendly technologies, materials and production techniques. The result is an increase in aggregated societal benefit, which is initially generated by an increase in socio-economic benefit and progressively by a gradual increase in environmental benefit.

The second path is essentially based on the use of technology (green technology development path), which first increases the environmental benefit. The development of new and environmentally friendly technologies is initially associated with high costs, meaning that their use in the market necessitates significantly higher product prices. With increasing scaling of the product in the life cycle as well as further technological progress, which makes the application of this technology more favorable, cost advantages can also be generated in the market, thus increasing the socio-economic benefit as well. Following Figure 9, the green technology development path of AFI in the market initially displays an upward movement and only in the course of a movement to the right. Accordingly, and contrary to the affordability development path, an increase in aggregated societal benefit initially results in an increase in environmental benefit and, in the course of time, also in an increase in socio-economic benefit.

It can be deduced from the literature that these development paths can be placed in the context of geography and industry, among other factors. In general, it can be assumed that the affordability development path applies predominantly to products in emerging markets such as India and China (Chen & Wen, 2016; Ernst et al., 2015; Liefner & Losacker, 2020). The size of the market makes it easier to generate economies of scale and thus offers a higher potential. At the same time, it is likely that the urgency of cost reduction and low-cost supply to lower-income populations plays a greater role in these countries. The majority of the literature on frugal innovations revolves around this very issue. At the core of this is not only the technological solution, but also the simple reduction of functions to serve the BoP and, together with economies of scale, to generate cost advantages for greater demand (Prabhu, 2017). On the other hand, there is reason to believe that products from industrialized economies are more likely to increase the aggregated societal benefit via the technological development path and become AFI. The main reason for this is the technological demand of new product development, especially with regard to the complexity of the development of AFI. Better networking of actors in innovation

systems in industrialized economies can therefore be classified as a crucial factor (Barnikol & Liefner, 2022). At the same time, regulations and infrastructure are further factors that can geographically determine the emergence of AFIs (Barnikol & Liefner, 2022; Rennings, 2000). However, these factors do not automatically have the same effect on products, but can have a differentiated effect on product types and industries.

The detailed view, in addition to the broad geographic view, may underscore the need for an additional industry perspective on the hypothesis. Accordingly, the need for sustainable and cost-effective products can vary between industries depending on customers, geography and opportunities (Barnikol & Liefner, 2022). At the same time, the establishment of certain non-frugal techniques in a socio-technical regime may inhibit their development (see Fuenfschilling & Binz, 2018; Geels, 2002). Accordingly, there is a possibility that products for a niche market in particular may be more likely to be developed via the green technology path due to a lack of scalability and possibly specific environmentally friendly demand. An indication of this is provided by Figure 8, which shows that smaller companies tend to offer more environmentally friendly but more expensive products. In contrast, it is conceivable, especially for established products that are not in niche markets, that the environmental friendliness of existing scaling will be increased afterwards, as can currently be observed in vehicle manufacturing, with extensive regulatory guidelines on emission reduction in recent years and the switch to electric vehicles. Accordingly, it could be more likely that the affordability development path can be outlined for these products.

The geographical and sectoral context of the hypothetical development paths shows that there can be a certain blurring of the areas of application. Accordingly, the context still seems to be an important determinant for the development of (A)FI.

3.6 Conclusion

In order to answer the first research question, this paper has proposed an approach for assessing the degree of frugality of a product and a population of products and for showing the connection between product design and frugality. The approach can be flexibly applied to different industries and groups of products by adapting the design variables. It offers a way to categorize products and to develop hypotheses about paths of product development. Concerning the second research question, this paper has

characterized a sample of products regarding their frugal features, establishing empirical evidence regarding the range of frugal and non-frugal features to be found.

This paper's findings will be relevant for the future development of the field of frugal innovation research for different reasons. Firstly, it is becoming clear that empirical research using samples of products and producers will help to gain insights that could not have been established with case study research or conceptual work alone. Empirical research can be used to test concepts and to discover empirical phenomena. It will thus help to increase public awareness of the potentially great benefits of AFI. Secondly, the particular method of assessing frugality proposed here will stimulate further research that may use and improve or challenge and overcome the methods used here. Thirdly, the research results indicate that a straight development path towards AFI may be difficult to take. Development routes may prevail that stress one aspect first – environmental or social – and add the other one later in the product life cycle.

This paper's research shows some marked limitations. Sample size is limited, the range of high-income country companies and products examined is only a small fraction of the FI world, and the variables used may become more refined in the future. The methods used here have been largely descriptive, leaving ample room for truly analytical approaches. Further research may thus aim to establish larger samples including different industries. Furthermore, the data used do not provide enough evidence and depth of explanation to support the hypotheses stated here. However, they offer a sound starting point from which to pursue the hypotheses. An international comparative analysis and the consideration of different product versions at different points in time are necessary. In addition to quantitative analyses, multiple case studies can also be used to test the hypotheses.

Despite the limitations and the need for further research, some careful policy recommendations can be provided. Firstly, companies and policy should look into the potential for AFI, regardless of whether they consider themselves advanced or emerging. Going frugal does not necessarily mean approaching low-income markets right away. Targeting environmentally concerned customers in high-income countries with AFI that come at a high cost – at least initially, before scale economies bring prices down – may be the more natural approach for companies in advanced markets. Advanced frugal innovations may thus be more likely to serve the needs of high-income

countries and may have greater potential in these markets than frugal innovation. However, it is clear that the development of AFIs is not easy and, in addition to technological challenges, that there are also institutional ones to consider. Their positive aggregated societal effects will nevertheless make them a much appreciated product category, and policy should thus help to spread information about AFI among users and help companies to build the qualifications to frugalize their products and come up with novel AFI. In addition, research needs to further elaborate on what other frugal design principles there could be and how they interact in the context of the different benefit dimensions.

CHAPTER FOUR

Green and Competitive: Who influences the development of advanced frugal product characteristics?

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Status: This Chapter is submitted to *Technology Analysis & Strategic Management*

Abstract

The societal shift to a greener economy is subject to a trade-off. Green products are often more expensive than conventional products, making them less attractive and thus slowing down the transition. Advanced Frugal Innovations overcome this trade-off and are able to accelerate the transition through the inclusion of broader population groups. Based on a company survey, this research examines the influence of societal actors on green and cost-related product attributes that influence this trade-off using correlation analyses and meaningful illustrations. Using the German manufacturing sector as an example, this new database provides first empirical results that illustrate how societal and systemic agents affect the development of green and competitive products and accelerate the transition to a greener economy. The results indicate that the societal and systemic situation in Germany has an inhibiting effect. Because the majority of agents favor the development of green products but weaken their competitiveness.

Acknowledgments

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4.1 Introduction

Global emissions of CO_2 and other climate-damaging and polluting gases continue to rise as well as the consumption of fossil raw materials. The transformation to green product development faces this critical situation, but creating green technologies and expanding green infrastructure is often expensive. High costs can inhibit the acceptance (Park, 2019) and speed of an overall economic transformation process.

Overcoming this trade-off that Porter and Van Der Linde (1995a, 1995b) already address is key to a sustainable transformation in which the broad population of economies with different financial and technological starting conditions can be taken along. The approaches that Porter and Van Der Linde (1995a, 1995b) developed occur in a similarly form in the context of frugal innovation. More specifically, production and development side frugality approaches through advanced technologies, salvaging from end of life, and simple design can also resolve the trade-off (Rao, 2017c, 2018, 2019, 2022). These principles, which can also be applied to non-physical products, lead to a form of innovation that can be described as green and competitive according to (Barnikol & Liefner, 2022). Combining the use of advanced technologies and frugal design, these new or revised products are called advanced frugal innovation.

Previous research discusses that the conditions for the emergence of AFIs are not solely due to the capabilities in the development process but are also subject to social conditions (Barnikol & Liefner, 2022). This makes them more complex than other frugal innovations, which react to financial constraints in less developed countries (Gupta, 2012, 2013; Prahalad, 2012). The environmental aspect is often ignored in this general definition (Hossain, 2021a). Recent research increasingly considers the environmental aspect and puts it on a par with cost savings (e.g. Albert, 2019; Barnikol & Liefner, 2022; Brem, 2017; De Marchi, Pineda-Escobar, et al., 2022; Liefner et al., 2020). However, since this combination involves specialized and comprehensive knowledge of the impact of technologies, highly skilled personnel and effective sharing of relevant knowledge are required (Rao, 2017a). The evolution of the research field FI from a focus on low-income households or lack of access to infrastructure to an added value for high-income households in the form of AFI benefits society as a whole. Furthermore, it qualifies AFI to help pave the way to a greener economy. The ability to develop AFIs can be seen as a key competitive advantage for companies, regions and economies.

To take a closer look at the solution of the trade-off and the societal framework conditions, this Article relies on an explorative research design. To this end, building on existing theoretical constructs, societal agents are identified from the literature and their influence on green and competitiveness-determining product attributes are investigated. Since there is still little prior empirical work on this topic and accordingly no empirical data on how individual agents and society influence these attributes, the research approach can be classified as exploratory. Two research questions are investigated: (RQ1) How does the systemic embeddedness of a company influence the development of AFIs? Do systemic agents have an inhibiting or facilitating effect (RQ2)?

To answer the research questions, primary data from a company survey in the manufacturing industry in the two German states of Lower Saxony and Hesse are examined. With the help of simple correlation analyses as well as suitable representations, correlations between the agents' aspirations and the actual product characteristics can be drawn. The results indicate that the societal and systemic environment influences the development of AFIs, but this influence is not uniform and creates a product-specific trade-off that can be linked to the systemic and societal constellation. To explore the compatibility of affordable and green products from a systemic perspective and to answer the research questions, the paper is structured as follows. First, Chapter 4.2 discusses the theoretical background and identifies agents that can play a role in the development of AFIs in the manufacturing sector. Chapter 4.3 includes the formation of aggregates in terms of product costs and sustainability, which are related to the agents' efforts in Chapter 4.4. In the discussion in Chapter 4.5, these results are interpreted and placed in the context of existing literature. The main results, recommendations for action and the need for future research are the subject of Chapter 4.6.

4.2 Theory

The term advanced frugal innovation (AFI) describes products with a more comprehensive degree of complexity in the research field of frugal innovation. In contrast to unrefined frugal innovation (UFI), they have a greater need for a supportive environment. Their development requires, among other things, acceptance of frugal design principles (FDP) and technological capabilities (Barnikol & Liefner, 2022). Accordingly, the ability to develop AFIs is determined not only by factors internal to the

company but also by external factors. This results from the characteristics of AFIs as well as the innovation system-related and institutional prerequisites for the development of this special form of innovation. Furthermore it may create the capability to escape the trade-off between competitive prices and green product characteristics.

4.2.1 Advanced Frugal Innovation

AFI's technological claim is based on the agreement between environmental sustainability and competitive prices. In the case of frugal innovations, cost savings are essentially generated by concentration on core functions and an optimization of the performance level (Barnikol & Liefner, 2022; Weyrauch & Herstatt, 2016). Products are simplified to such an extent that they become affordable even for low-income groups (Hossain, 2020, 2021a; Prahalad, 2012; Rao, 2013; Sinkovics et al., 2014). Although there are frugal innovations that result in lower CO_2 emissions and are more environmentally friendly than competing products (Albert, 2019), research often neglects negative externalities that can lead to a shift of costs to the non-monetary sphere and thus have negative effects on the health and natural as well as societal environment of consumers (Barnikol & Liefner, 2022; Hossain, 2021a). Barnikol and Liefner (2022) consequently refer to this form as unrefined frugal innovation, as such products merely shift costs and do not create environmental and socio-economic benefits in a positive balance. Combining the claim of cost efficiency and environmental friendliness of products, AFI, on the other hand, can create an overall benefit for society. Accordingly, AFI often also represent environmental innovations, which can enable, accelerate and simplify the transition to a sustainable economy through lower or competitive prices.

However, these dimensions increase the demand for development and require fundamental knowledge of the product, the area of application and the customers (e.g. Jha and Krishnan, 2013) as well as technical capabilities with a highly skilled workforce (Rao, 2017a). From an engineering perspective, there is only one comprehensive approach that serves the targeted frugalization of sophisticated products at the moment. The Factor of Frugality (Rao, 2017c, 2018, 2019, 2022) is a guideline for the development of new products and for the revision of existing products. Based on a simple design, modern technologies and materials, adjustments in the production process, and application of the 4R principles, the material input of a product is optimized, thus realizing significant cost savings. The resulting products are often

lighter and have a longer life span, which in turn reduces energy consumption and has an additional positive environmental effect (Rao, 2019). Other approaches, technologies and business models already exist that can enable the development of AFI or, in combination with the Factor of Frugality, can bring further benefits but have not yet been associated with frugal design principles and AFI (e.g. Arnold et al., 2018; Bocken and Short, 2016; Liechty et al., 2023; Mecklenburg et al., 2012).

4.2.2 Relevance of innovation systems, socio-technical regime and institutional embeddedness

The factor of frugality can be applied to all physical products, and frugal design principles in general may go beyond them. The need for suitable materials, specified knowledge and technologies limits the range of users and scope of application nevertheless. Knowledge about potential materials and technologies, and the necessary infrastructure must be available but can be expensive. These conditions vary geographically and require not only technological capability but also a societal and innovation system perspective as Barnikol and Liefner (2022) discuss.

Innovation systems represent a network of different agents interacting with each other that is held together by common institutions (Edquist, 1998; Kline & Rosenberg, 1986). For the emergence of AFI, two types of innovation systems as particularly relevant: Territorial Innovation Systems including National (Freeman, 1995) and Regional Innovation Systems (Cooke et al., 1997), and Technological Innovation Systems (Carlsson & Stankiewicz, 1991). For both types of innovation systems, different agents indeed influence the possibilities and characteristics of the final product. The more agents support the development of AFI in an innovation system, the higher is the probability that they will be actually realized (Barnikol & Liefner, 2022).

In the context of AFIs, Barnikol and Liefner (2022) identify five agents as relevant: Customers, suppliers and cooperation partners, research institutes, governments and the innovating companies themselves. The basic idea is that the more of these agents support the development of AFIs, the more frugal the products of the companies involved in the corresponding innovation systems will be. There is a need for companies that are able to develop AFIs, suppliers that can offer frugal components and materials, research institutes that develop the fundamentals of new technologies and discover modern lightweight and robust materials, state agents that reinforce the development of these products and support them with suitable regulations and

infrastructure, and above all customers who want to consume these products (Cooke, 2001a, 2001b, 2001c). The agents not only influence the innovating company and its products but also their environment and other agents in the innovation system. That makes the innovation system more akin to a network of an innovation-supporting or -hindering environment. This can go to the extent of forming mission-oriented innovation systems (MIS) that pursue a clear aim and, for example, work towards the development of products with certain characteristics (Hekkert et al., 2020; Wanzenböck et al., 2020). The new MIS concept could provide a better theoretical basis for the development of AFIs in the future.

In addition to the provision and availability of technological properties, legitimacy must also be created for new products and technologies, or for the application and necessity of frugal design principles in development processes. Individual agents can create legitimacy for their application in this context (Hekkert et al., 2007). Policymakers can legitimize the orientation of research institutes (Fischer et al., 2020) and support them through funding. Conversely, scientists can also draw the attention of policymakers to technological needs and opportunities alongside companies. Companies can develop products that serve as a flagship for this type of product. In the case of AFI and the combination of reducing resources and costs, this is a significant factor. For example/instance, striving for the next higher percentage of performance in mechanical and plant engineering in Germany often contradicts cost- and resource-efficient solutions. Additionally the widespread conviction that green products are premium products and must therefore be more expensive than conventional ones is prevalent (Berger, 2019). In this context, the mechanisms of product development and those of training and education are relevant factors to consider. The development and market penetration of AFIs would therefore also have to be accompanied by a social change that enables logic and action beyond a trade-off between the environment and monetary costs and considers this as standard. The acceptance of AFIs and the application of FDPs is therefore linked to a specific institutional framework.

The existence of institutions is strongly influenced by regional conditions, among other factors. Climatic conditions, natural disasters, topography and biogeography can influence the rules of living together in a society. The resulting institutions can constitute a significant locational advantage for the economic development of a region (Olsson, 2005). At the same time, institutions can also be influenced by circumstances

in adjacent countries, such as political instability, poverty and others (North, 1990; Simmons & Elkins, 2004). In particular, economic conditions and the concomitant need for more modest consumption shaped the capacity for simplification in countries such as India, making it a lead market for frugal innovation (Tiwari, 2017). The cultural-cognitive perspective on the products' socio-economic benefits is therefore particularly pronounced in emerging economies (Ananthram & Chan, 2019; Gupta, 2012). Barnikol and Liefner (2022) argue that technological and systemic capabilities in contrast are more emphasized in advanced economies. Since the cultural-cognitive perspective on AFIs also requires an environmental component, it is debatable of this is a geographical advantage for advanced economies which may facilitate the transition towards a green economy by invalidating the trade-off.

Conducive institutions and the ability to generate relevant knowledge, transfer it to suitable recipients, and transform it into new products are primarily regional. This leads to the assumption that these characteristics and capabilities, which are necessary for the emergence of AFIs and for overcoming the trade-off between monetary and environmental costs, differ geographically and are determined by the support of systemic agents.

4.2.3 Choice of agents considered

The choice of agents considered is based on the combination of institutional framework conditions and the agents of the innovation system. It should be noted that the survey was only conducted among companies so that the perspective of the companies must be regarded. For this purpose, company-related motivation/ability and the motivation/ability of agents external to the company are relevant.

Among the company-related variables, the influence of shareholders, product developers, and the companies brand are taken into account. The consideration of these three agents is interesting regarding the coverage of different aspects of the companies orientation. Shareholders, for example, can change the focus of a company. This includes family-run companies, which are common in the German manufacturing sector, and public limited companies. About environmental friendliness, there is already empirical evidence of the power of shareholders (Bauer et al., 2022). Also the capabilities and aspirations of product development teams, who share values and convictions and have gained experience and behavior in respective companies or training institutes, matter. The brand represents the internal and external perception of

the company, and may also determine the design of the products and competitiveness through pricing.

The choice of influencing agents beyond the company under consideration is essentially based on the agents relevant to AFIs mentioned by Barnikol and Liefner (2022). These include governments, science, suppliers, cooperation partners and customers. The importance of these agents is illustrated in Chapter 4.2.2. Their influence in the examined target group can be considered negligible. For the variables mentioned, the influence of the respective agent on the variables listed in Table 8 was queried.

4.3 AFI Measurement and Aggregation

The methodology used in this paper is mainly based on the definitional work of Barnikol and Liefner (2022). To understand the empirical results, it is helpful to clarify the two methodological steps: data collection, and AFI measurement and aggregation. The data set of this paper is the result of a survey from 2022 in the months of May, June and July. Accordingly, the data derives from the same data set already used in Chapter 3. The questionnaire used for the company survey was tested in advance with company representatives and discussed with representatives of associations, ministries and consultancies.

At present, many approaches to measuring frugal innovation exist, but they are not suitable for measuring AFIs (see AlMulhim, 2021; Altgilbers et al., 2020; Dost et al., 2019; Dwiedienawati et al., 2021; Iqbal et al., 2020; Kronemeyer et al., 2021, 2020; Ploeg et al., 2020; Rossetto et al., 2017; Santos et al., 2020). Barnikol and Liefner (2022) therefore propose their measurement concept to capture AFI. This concept defines AFI as a continuum along the aggregated societal benefits. This is based on the two dimensions of environmental benefit (EB) and socio-economic benefit (SEB), which constitute the objectives of AFI described in Chapter 4.2 and are in a trade-off in the case of non-AFIs. These two dimensions also represent latent variables that must be captured with the help of proxy variables. The advantage of this approach is that these variables can be flexibly adjusted between sectors and product types, and that the higher levels of environmental and socio-economic benefit remain comparable. The same applies to the aggregated societal benefit (ASB), which represents the degree of innovation and efficiency between the two dimensions, and the market

novelty in terms of overcoming the trade-off. In general, all products with a positive ASB can be considered as AFIs due to the newly created efficiency compared to competitors. The difficulty, however, lies in the choice of suitable proxy variables. Since the data set is the same as in Chapter 3 dealing with the same products and the same industry, the same variables and aggregation methodology were used based on the derivation given in Chapter 3.3.

Within the scope of the survey, the respondents were asked to compare the characteristics of their products to the average products of the competition. The results were plotted on a 7-point Likert scale from much lower (1) to equal (4) to much higher (7). Finally, the results were transformed into a scale from -3 to 3 for further statistical processing. The aggregation of the three dimensions socio-economic, environmental and aggregated societal benefit is calculated as follows:

$$(1)\ Socio-Economic\ Benefit = \overline{SEB} = \frac{-1}{n} * \sum_{i=1}^{n} SEB_i = \frac{-SePr - MOCU}{2}$$

$$(2)\ Environmental\ Benefit = \overline{EB} = \frac{1}{n} * \sum_{i=1}^{n} EB_i = \frac{EFPU + SMPU + Ao4R}{3}$$

$$(3)\ Aggregated\ Societal\ Benefit = \overline{ASB} = \frac{1}{n} * \sum_{i=1}^{n} ASB_i = \frac{\overline{EB} + \overline{SEB}}{2}$$

The expression of the dimensions can be interpreted similarly to the initial variables. Increasingly negative values signal a negative effect compared to the competition. Negative effects can be higher product costs (SEB), higher environmental damage (EB) and a negative combination of both (ASB). Zero signals a similar effect as the competition. In the case of ASB, this can also happen if the EB is higher but is accompanied by a similar negative SEB. Barnikol and Liefner (2022) describe such a case as a shift in costs, which does not represent an innovative added value. Increasingly positive values signal a positive effect of a product compared to products of the competition. The location and distribution of the products by dimensions and proxy variables are shown in Table 8.

Table 8: Measurement variables for environmental and socio-economic benefits

	Mean	SD	Span
Aggregated-Societal Benefit (ASB)	***0.11***	***0.58***	***3.83***
Socio-Economic Benefit (SEB)	***-0.29***	***0.80***	***4.00***
Selling Price (SePr)	*0.56*	*1.23*	*6.00*
Maintenance and Operation Cost in use (MOCU)	*0.02*	*0.81*	*4.00*
Environmental Benefit (EB)	***0.51***	***1.02***	***5.67***
Environmental Friendliness of Production and use regarding energy (EFPU)	*0.79*	*1.21*	*5.00*
Use of Sustainable Materials in Production and Use (SMPU)	*0.41*	*1.12*	*6.00*
Use of 4R Mechanisms (Ao4R)	*0.32*	*1.09*	*6.00*

Based on the same formulas, the influence of the agents considered on the individual product characteristics can also be determined. Positive values indicate a favorable and negative values indicate a detrimental influence on the expression of the dimension.

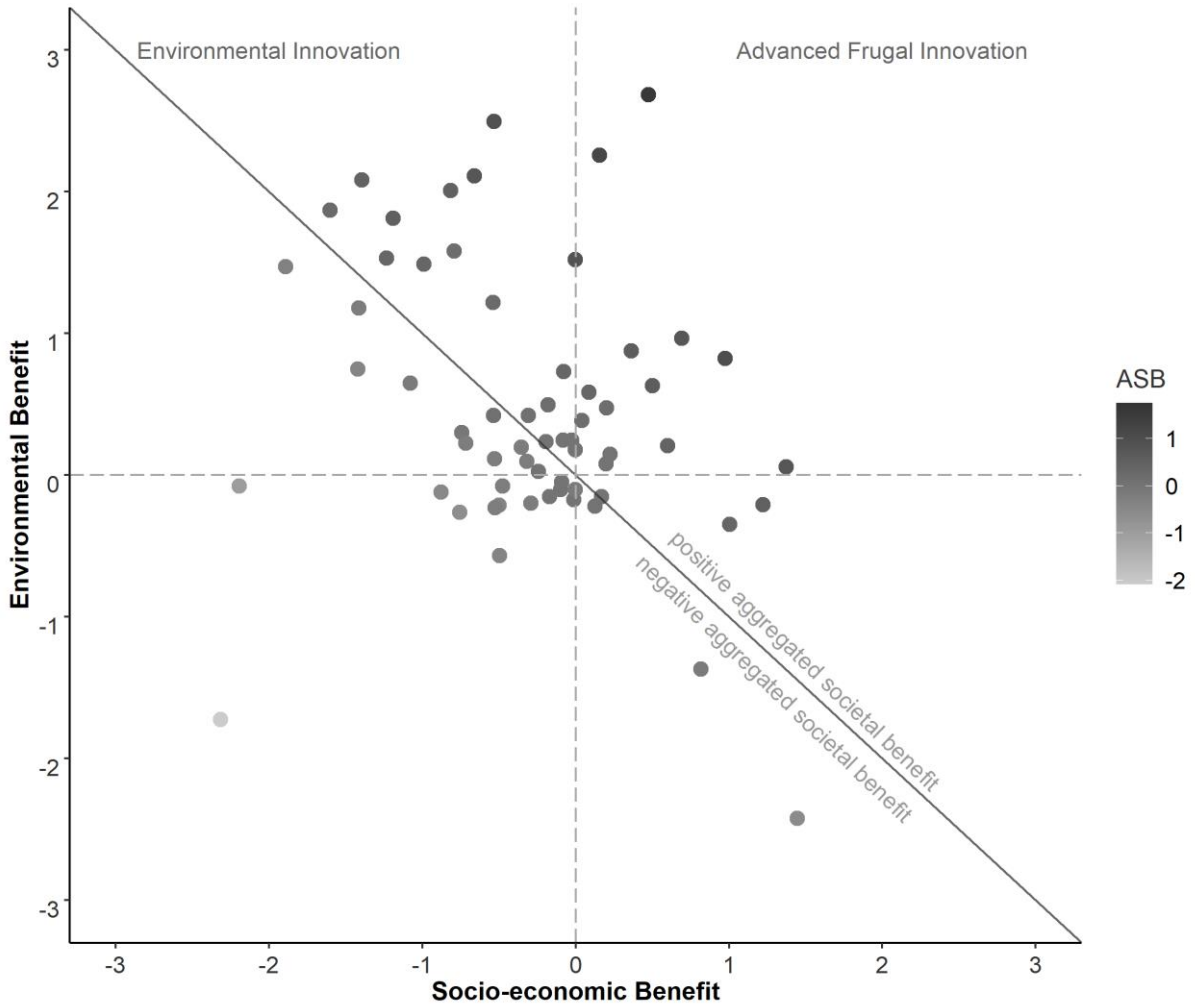
4.4 Results

The aggregation of the data enables the explorative investigation of the influence of different internal and external agents on the AFI-related product characteristics. For this purpose, the statistical correlations are examined and the orientation of the different agents is considered with regard to the direction of the effect and the strength of the influence. For a sufficient interpretation of the systemic components, it is first necessary to consider the distribution of products in the context of AFIs.

Figure 10 shows the distribution of the products of 63 companies regarding the two dimensions of environmental benefit and socio-economic benefit. The upper half includes products with a positive environmental benefit while the lower half shows a negative environmental benefit compared to the competition. From a socio-economic perspective, products on the right generate a positive benefit while products on the left generate a negative benefit. The diagonal line distinguishes products with a positive from products with a negative aggregated societal benefit. All products above this diagonal can be described as AFI, as these products represent a new efficiency or

innovativeness compared to the competition. It is apparent that the distribution of products in the manufacturing sector in the population of German companies tends towards positive environmental but negative socio-economic benefits. There seems to be a trade-off between these two dimensions in most cases. Nevertheless, some products have high ASB and express their innovativeness through a significantly more successful combination of both dimensions compared to the competition.

Figure 10: Aggregated societal benefit and trade-off between environment and socio-economic benefits in the manufacturing industry



Representation was created using the jittered method to better represent the distribution.

The detection of the systemic influence on the development of AFIs indicates a first tendency. In this context, the general consideration of the correlations regarding ASB and the specific correlations with regard to SEB and EB should be considered. In this context, it should be noted that the results refer to the case of the manufacturing sector

in Hesse and Lower Saxony. The influence of individual variables can differ between sectors, over time and in particular geographical areas. In addition, the statistical empirical possibility is subject to restrictions due to the low number of cases, in particular with regard to the choice of methodology. In this Chapter, therefore, the bilateral relationship between the agents and product-related frugality indicators is determined using Pearson's correlation. Despite the bilateral measurement, an overview of the systemic prerequisites can be determined.

Table 9: Correlation between internal and external agents and the ASB of the product

	P	*C*	*SCo*	*Sc*	*Gov*	*Sh*	*Pd*	*B*
Product (P)	1							
Costumer (C)	**0.35*** **	1						
Supplier and Cooperator (SCo)	**0.50*** **	**0.65*** **	1					
Science (Sc)	**0.33*** **	**0.38*** **	**0.47*** **	1				
Government (Gov)	-0.23*	0.08	0.03	-0.21*	1			
Shareholder (Sh)	0.24*	**0.41*** **	**0.38*** **	**0.26** **	**0.27** **	1		
Product developer (Pd)	0.18	**0.42*** **	**0.43*** **	0.10	**0.34*** **	**0.51*** **	1	
Brand (B)	**0.45*** **	**0.44*** **	**0.54*** **	**0.40*** **	0	**0.51*** **	**0.40*** **	1
N=63, *<0.01, **<0.05,***<0.01 according to Pearson								

There is a systemic connection in the case of the manufacturing sector in Lower Saxony and Hesse. In this context, Table 9 shows the correlation between the ASB-related aspirations of the individual agents and the ASB-related actual properties of the product and each other. Interpretatively, this represents the extent to which the individual agents support (positive correlation) or counteract (negative correlation) the AFI-related innovativeness of the product. Although it is evident that not all influencing agents surveyed have a connection with the product characteristics, at least a direct and indirect connection of the agents with the product characteristics can be drawn. Especially in the case of significant ($p<0.05$) correlations, the product characteristics are more in line with the agents' expectations. In these cases, the agents benefit from each other directly and indirectly to the same extent as the characteristics of the products. In detail, the brand is the only significant company-related agent influencing product characteristics. Of the external agents, customers, suppliers, cooperation partners and science have a significant direct influence. Shareholders, product developers and the government have no significant connection with the AFI-related product characteristics, but Shareholders and product developers show evidence of

positive correlations with the other directly to the product variable connected agents. Government shows only significant correlations with shareholders and product developers (Table 9).

Table 10: Correlation between internal and external agents and the SEB of the product

	P	*C*	*SCo*	*Sc*	*Gov*	*Sh*	*Pd*	*B*
Product (P)	1							
Costumer (C)	0.17	1						
Supplier and Cooperator (SCo)	**0.29****	**0.51*****	1					
Science (Sc)	0.05	0.20	0.18	1				
Government (Gov)	-0.03	**0.29****	0.23*	**0.52*****	1			
Shareholder (Sh)	0.15	0.23*	**0.47*****	0.08	**0.42*****	1		
Product developer (Pd)	0.04	0.23*	**0.27****	0.10	0.05	0.22*	1	
Brand (B)	***0.35*****	*0.09*	***0.38*****	*0.13*	*0.07*	***0.34*****	***0.32****	*1*
N=63, *<0.01, **<0.05,***<0.01 according to Pearson								

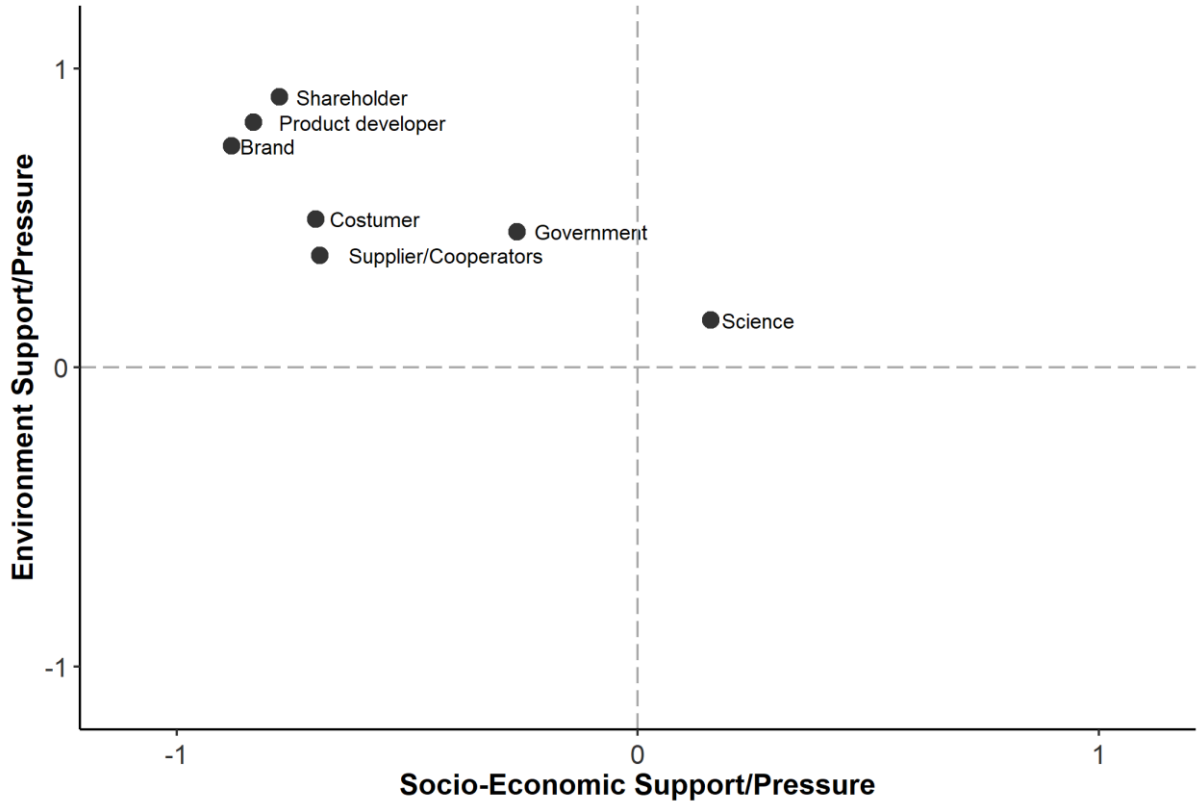
Table 11: Correlation between internal and external agents and the EB of the product

	P	*C*	*SCo*	*Sc*	*Gov*	*Sh*	*Pd*	*B*
Product (P)	1							
Costumer (C)	**0.65*****	1						
Supplier and Cooperator (SCo)	**0.60*****	**0.76*****	1					
Science (Sc)	**0.32*****	**0.37*****	**0.54*****	1				
Government (Gov)	0.21	**0.34*****	**0.45*****	**0.36*****	1			
Shareholder (Sh)	**0.55*****	**0.53*****	**0.59*****	**0.30****	**0.33*****	1		
Product developer (Pd)	**0.37*****	**0.27****	**0.31****	0.23*	**0.32****	**0.31****	1	
Brand (B)	**0.63*****	**0.67*****	**0.61*****	**0.39*****	0.22*	**0.49*****	**0.49*****	1
N=63, *<0.01, **<0.05,***<0.01 according to Pearson								

The individual analysis of the SEB (Table 10) and EB (Table 11) dimensions shows that the strength and significance of the individual relationships deviate significantly from the aggregate. Concerning the SEB (Table 10), only the supplier and cooperation partner and the company's brand correlate significantly. This suggests that pricing is largely influenced by the company itself rather than being externally driven. The scalability of the products and the market segments in which the company operates could have a greater influence. The situation differs about environmental benefits (Table 11). All variables, apart from government, show a significant correlation. Therefore, the environmental benefit of a product depends more on internal and

external agents than the socio-economic benefit. At the same time, the variables in Table 11 showing significant correlations in almost the complete matrix. A general comparison of Table 11 with Table 9 and Table 10, shows that the correlations are stronger in the case of the EB and weaker in the ASB due to the weaker and absent correlations of the SEB.

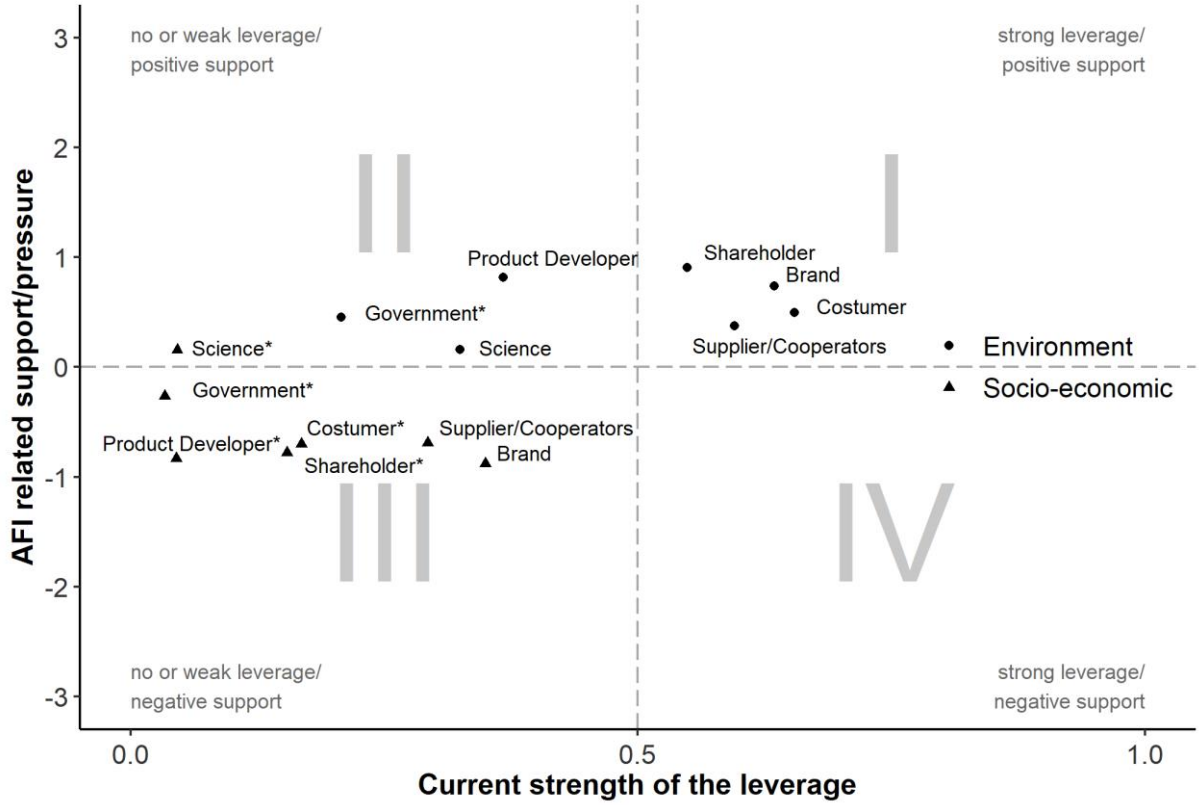
Figure 11: Agent-side trade-off between environment and socio-economic benefits



In addition to the actual correlations, the data also provide information on the direction of influence. Figure 11 shows the position of the systemic indicators in terms of environmental support and socio-economic support. The expression of the individual variables is the result of mean values across the data set. It conveys to what extent individual agents or the company's brand exert pressure on the product characteristics. Positive socio-economic pressure signals that agents demand or favor lower product costs, while negative pressure represents a favor for higher product costs. At the same time, positive environmental pressure marks environmentally friendly behavior, such as the use of sustainable materials and energy, while negative pressure stands for environmentally harmful behavior. Except science, all agents are located in the second

quadrant and accordingly exert positive pressure on environmentally friendly behavior, but simultaneously favor a negative socio-economic effect. This relationship is stronger in the case of internal agents' brands, shareholders, and product developers, but in the case of external agents' consumers, governments, suppliers, and cooperation partners. Science is particularly noteworthy as it only slightly favors the environmental friendliness of a product as well as its affordability.

Figure 12: Strength and direction of support for AFIs by societal agents



**The statistically measured correlation does not reach a significance level of $p < 0.05$ (see Table 10 and Table 11).*

While Table 11 only shows the correlation and Figure 11 shows the direction of the actual influence, Figure 12 shows a synergy of both findings. The AFI-related pressure and the strength of the influence are compared. The AFI related pressure represents the direction like Figure 11, whereby the illustration of the agents indicates the expression regarding EV and SEB according to the legend. The current strength of leverage represents the correlations with the product characteristics from Table 10 and Table 11. It should be noted that these are only positive correlation coefficients. The relationship between the government and the product with regard to the socio-

economic benefit is negative at -0.03. In this case, it is shown in absolute terms because the relationship is still statistically non-existent, but the agent can be integrated. The representation of larger numbers and negative significant correlation coefficients would have to be adjusted. Accordingly, the figure shows if an agent has an influence and whether this influence favors or hinders the development of AFIs.

An aid to interpretation is the consideration of the quadrants. Quadrant I represents agents and factors with a high and facilitating influence. Quadrant II includes AFI supporting agents and factors with weak or no influence. Quadrant III represents AFI adversaries with no or weak influence. Quadrant IV contains high-influence counterparts. The company's brand and the agents are located entirely in quadrants I and II in respect of environmental benefit, while they are predominantly positioned in quadrant III in respect of socio-economic benefit. In an ideal systemic situation that supports AFI, all agents and dimensions would be positioned in the I quadrant in a systemic AFI-supporting situation. Decision-makers who want to develop or promote AFIs should consequently try to shift their position in this direction.

4.5 Discussion

Despite the low number of cases, the results presented in Chapter 4.4 show significant and reliable results. Nevertheless, it must be minded that the questionnaires were filled out by company representatives and therefore capture only their perspective on the individual agents. It can be assumed that they still correspond most closely to reality as an intermediary between the agents. The results show that the systemic prerequisites for the development of AFIs and the creation of the highest possible ASB turn out very different.

Superficially, the development of AFIs from a systemic perspective benefits from a general movement towards environmentally friendly product characteristics of individual agents, which is evident in Figure 11. This is also supported by the associated positive effects of the environmental performance of AFIs in the entire matrix of Table 11. In the case of the Socio-Economic Benefit (Table 10), this can be observed to a much lesser extent. The trade-off between the two dimensions thus appears to be institutionally supported. This explains why the companies in their overall competitive dispersion predominantly position themselves along the trade-off line of the ASB, and why the pattern in favor of the environmental benefit is like that of the

systemic agents (see the comparison between Figure 10 and Figure 11). More Recent work supports this finding, noting that for green product innovation, cooperation with civil society and market influence are critical (Cassetta et al., 2023). The ability to innovate in relation to the development of AFIs is thus clearly diminished.

From an external perspective, this result fits society's aspirations towards a climate-friendly and environmentally friendly economy. For example, the environmental awareness has been increasing in Germany (Umweltbundesamt, 2022). Another argumentation is that green products are often understood as premium products and this is also reflected in the prices of products. Berger (2019) essentially justifies this with the signal theory, which explains the consumption of green products as a status symbol that is indicated by a price difference. This can also be linked to a logic of customers of internalizing negative external effects in the price of the product, as a necessity to make the product environmentally friendly in the first place. Schwirplies and Ziegler (2016) show that environmentally conscious consumers in Germany are more motivated to spend money on carbon offsets than consumers in the United States, which indicates that this mechanism varies regionally and might be stronger in Germany than in other countries. Either reason can explain the positioning of customers. An example for a governmental influence on the trade-off are particulate filters in cars. This additional technology serves to increase environmental compatibility, but may result in higher product prices due to the passing on of the additional costs for upgrading a previously not used technology. This type of regulations by governments, and the setting of comparable standards in the development of products can also be seen as an example of how the government promotes environmental benefits while reducing socio-economic benefits. Separate from this, laws and regulations support only one of the two dimensions. Research institutes and universities are the only agents in the Hessian and Lower Saxon manufacturing sector that have a positive impact on both dimensions. Compared to governments and customers, this could be due to the kind of systemic and societal relationship. While companies must follow laws and regulations and react to customer demand rather than generate it on a large scale, companies have a greater influence on the type and the target direction of cooperation with universities and research institutes. Accordingly, the company can influence the extent to which the cost issue is taken into account, the research result plays a crucial role in the production and for the final product.

The company-related variables and the agent supplier and cooperation partner can be interpreted similarly as a totality of the companies. The current positioning of the products (Figure 10) and the company-related influencing factors as brand, shareholders and product developers (Figure 11) are linked to the systemic influence. Therefore, these are interpreted as the result of systemic influencing factors. The positioning as a premium product in international competition could be decisive here because it leads to the development of environmentally friendly products in companies and corresponding prices can be achieved for them. Especially if companies from countries with lower production costs (e.g. from Asia), compete little in their markets, there is less incentive to lower prices and these companies and products are protected by a unique selling proposition (Berger, 2019). In this context, the trade-off could also be strategic or psychologically institutional to a probably small but noteworthy extent. Increasing competition and better market transparency or consumer knowledge could counteract this. The similar positioning of suppliers can also be explained by this, as market knowledge is shared more easily, especially among cooperation partners (Bathelt et al., 2004), and should result in similar behavior.

In addition to discussing reasons for the current systemic situation, the question arises which constellation is necessary for the development of advanced frugal innovation, and to what extent the current situation can be changed. The results from Figure 12 are particularly interesting in this regard. While – except for science – the agents predominantly have a medium to strong and supportive influence on environmental benefit, the support turns negative with no to weak influence on the socio-economic benefit. It is important to note that the form of the survey and the presentation are new in the research field, and no comparable values are available. Comparable data from other countries and other markets would allow for a higher degree of certainty in the interpretation. The potential mobility of individual agents in terms of strength of their influence is largely dependent on the economic and social system in which they find themselves. Compared to Germany, China’s government is likely to have a significantly higher upper limit of a possible correlation coefficient and influence on product design. An ideal constellation would be a positioning of all agents in the I. and II. quadrants to create an AFI-supporting innovation system. This is a static perspective though; in the course of the innovation process and life cycle, the importance of the individual agents and the need for their support may vary (Dewald & Fromhold-

Eisebith, 2015). An ideal constellation can also arise if appropriate agents influence the development supportively at the right time.

The current constellation in Lower Saxony's and Hesse's manufacturing sector suggests that the positive environmental benefits of many products in competition are integrated into and subordinate to an overarching systemic and societal aspiration. Nevertheless, it can be assumed that the socio-economic benefits are more strongly influenced by companies that can be driven by their self-image as premium manufacturers. This is essentially characterized by the positioning of the brand showing the most negative and strongest trend. A change in society's understanding of quality to the effect that resource efficiency can be reflected in cheaper consumption and usage prices could increase the acceptance and assertiveness of AFIs. In this context, the consumer of Figure 12 would initially shift towards and into the II quadrant. In the medium to long term, consumers could be positioned in the I quadrant (in terms of environmental benefits), exerting positive and strong pressure in terms of socio-economic benefits. This mindset shift could have a similar effect on shareholders, suppliers and cooperators as well as product developers. The positioning of governments could also adjust in this context. The direction of impact and effectiveness of the measures should also be evaluated anyway. A change in the understanding of quality coupled with more efficient measures could, overall, resolve the systemic favoring of the trade-off.

From an international perspective, the current situation can be both: a strength and a weakness. Although there does not seem to be any price-reducing pressure in the observed systemic-social constellation in Lower Saxony and Hesse, it may exist in other countries, regions, sectors, companies or individual customer groups. The literature on classical frugal innovation underlines this by prioritizing the reduction of monetary costs to supply low-income consumer groups (Hossain, 2017; Lim & Fujimoto, 2019; Weyrauch & Herstatt, 2016; Zeschky et al., 2011). Barnikol and Liefner (2022) argue that, principally, the ability to develop both green products and low-cost products is a strategic starting point for the development of AFIs. The ability to provide green and affordable products to broad consumer groups will be an increasing competitive advantage for companies and regions.

Companies, especially in the German market, could strategically develop green products that are perceived as premium in the short to medium term, and use the

resulting revenues to expand competitiveness in the direction of lower-cost products. In the medium to long term, however, they will need to generate environmentally friendly and low-cost products to prevail international. The respondents of our survey/ to our questionnaire believe that this ability helps German companies to ’re-conquer applications traditionally occupied by Far East products’ and to ‘clearly differentiate themselves from the competition through greater innovative strength and thus [create] market differentiation’. It also offers companies the opportunity to use a First Mover Advantage (see Lieberman and Montgomery, 1988). Since AFI, in contrast to FI, addresses a broader spectrum of markets and customer groups, the advantage could turn out to be greater than Zeschky et al. (2014) find for FI. One way to leverage this strategic advantage for Western companies could be to cooperate with companies from emerging economies that have experience in reducing costs and simplifying product design (Lim et al., 2013; Niroumand et al., 2020; Tiwari & Herstatt, 2012) to develop affordable but green products for emerging, and environmentally friendly but affordable products for advanced economies.

To facilitate this strategy for companies, regions and countries need to create an innovation infrastructure and transition to a societal acceptance and appreciation that supports the combination of environmental and socio-economic benefits in product development. To this end, it is necessary to enable behavioral adjustments and to implement measures that ensure better comparability of products in terms of environmental friendliness and cost-efficiency. It is crucial to apply measures that are low-cost but at the same time ensure optimal transparency. One possibility for that/ to do so would be an institutional framework in which environmentally harmful behavior is internalized in prices across all products in a market, as is the case with European emissions trading. According to Porter and Van Der Linde (1995), a competitive advantage could be generated if environmental regulations are tightened in other countries.

4.6 Conclusion

The aim of the scientific contribution is to explore essential findings on the relationship between innovation system agents and socially useful product characteristics from an environmental and socio-economic perspective. An essential part was to identify possible reasons for the observed trade-off between these dimensions. This trade-off can additionally be cited as a reason for a slower transition to a more environmentally

and climate-friendly economy, as higher prices for green products limit the overall societal participation in consumption and weaken the acceptance of transition. Consequently, this work shows that AFI can also be understood as an enabler of an accelerated transition in this context.

The conducted explorative study shows the influence of individual system agents on the characteristics of a product with regard to socio-economic and environmental benefits. The results indicate that a trade-off between these properties is strengthened by many agents in favor of green product properties and that higher prices are accepted or considered. It turns out that science or research-related cooperation is an exception in this mechanism and that a simultaneous promotion of both properties can be attributed. Consequently, using appropriate technologies and product designs can be a way of preventing the social product outcome from being too one-sided. The sustainability efforts, on the other hand, are particularly driven by consumers, the brand and suppliers. Suppliers and brands are also the agents who particularly weaken the socio-economic benefits through a price-increasing influence. From a systemic and societal perspective, it appears that the trade-off is also favored by institutional factors.

Based on the data used there is a correlation between the innovation system and societal expectations and perceptions of the characteristics of a product. The systemic situation in the manufacturing industry in Germany is not a favorable factor to completely escape a trade-off between green and affordable product characteristics. Nevertheless, the strong and consistent efforts of systemic agents to influence the environmental benefits point to a green technology development path that, according to Barnikol and Liefner (2022), has the potential to give rise to AFIs that are capable of resolving the trade-off. Transferred to the societal perspective, supplementary considering the cost side can create a situation that establishes the innovation form of AFI and enables the trade-off to be resolved. This would also significantly accelerate the transition towards a green economy. Whether the solution approach is essentially technologically, socio-cognitively or psychologically driven or more likely a combination of those cannot be finally determined with this research. In addition to available research this Article does support the assumption that societal perceptions of pricing in the context of a green economy have a negative feedback effect, slowing and hindering the transition towards a green economy and the development of AFIs. Expressed differently AFI efforts do not fail because of missing motivation to generate

green products but because of the motivation to reduce or remain the price level simultaneously. While most agents do not hinder the reduction of prices, they often do not encourage it either.

The results presented in this Article contribute to the research field of frugal innovation and to transition research from a theoretical and methodological perspective. In doing so, this work underpins the importance of AFIs for the transition to a green economy. The influence of societal and systemic agents on the development of green and affordable products was uncovered separately by direction and strength from a theoretical perspective. This enabled the identification of stakeholders' interests and degrees of impact that have a novelty degree for research on frugal innovations and also for the transition research in general. The methodologies and modes of presentation presented simplify the empirical investigation of related issues. Furthermore, the research results offer first-time observations on the societal and systemic influence on the development of advanced frugal innovation and frugal innovation in general.

However, the classification of the results is limited by the small sample size and the lack of comparable surveys and measures. Nevertheless, the dataset is unique and the results show expressive new empirical findings. To allow a better comparison of results, further research with a larger sample size, other industry and/or country focus has to be conducted. This would also show if the transition conditions for a greener economy and the implementation conditions for the development of AFIs in the German manufacturing sector represent an actual location-related advantage. This also refers to the influence of the agents and to the question of whether they are already exploiting their potential or need to develop it further. The present study can serve as an orientation framework that leaves room for expansion and adaptation.

Nevertheless, policy implications can already be derived from this study. Since agents influence the development of advanced frugal product characteristics and thus also determine the degree of a trade-off, they should use their influence to increase systemic competitiveness. In addition, the overall constellation of agents should be considered and, ideally, adjusted. This would also accelerate transition in industrialized economies like Germany. In order to steer the regional path towards the development of green and affordable products, education and training of labor is necessary and companies must be supported in dissolving unfavorable networks (see Kyllingstad,

2021). In this context, it can be useful to support start-ups and young companies that are more dynamic than traditional companies and can develop a more disruptive potential (Fu & Qian, 2023).

From an entrepreneurial perspective, the systemic constellation should be considered when the development strategy of a product is focused on the combination of green and affordable competitive products in the overall market. This development purpose should be embedded in a favorable systemic constellation, which is only partially given in the manufacturing sector in Germany. It is advisable for Western companies in particular to relearn the ability to develop low-cost products as competition from Far Asia increases (Ryans, 2015).

In conclusion, AFIs can contribute to a greener economy and, through their competitive and affordable character, can promote the transition to it. However, the societal and systemic conditions must change, and the monitoring and identification of possible adjustment mechanisms requires further research, being far from complete.

CHAPTER FIVE

Conclusion

This final Chapter summarizes the main findings of this dissertation. In addition, limitations, contributions to the research field, political and managerial implications, and the need for further research are addressed.

5.1 Summary of main findings

This dissertation investigates the conditions for the emergence of AFI on different scales. The explorative research design allows new insights and enables to formulate hypotheses that serve to answer the central research question: "Which framework conditions are necessary for frugality to prevail in innovation processes?"

Article 1 (Chapter 2) answers the research question from a theoretical perspective. Combining of research on AFI and innovation systems, and transition research enables to identify four factors from a societal and systemic perspective. The existence of a frugal mindset in connection with a frugal oriented institutional framework that facilitates acceptance and application of FDPs is fundamental. Based on this, it is helpful if as many agents as possible also aim at developing affordable and environmentally friendly products and implement them in their sectors. This ranges from development of technologies and materials used in a product to laws and standards. Furthermore, the emergence of AFI, as well as FI, can be understood as a response to scarcity. This also relates to the mitigation of negative environmental impacts. Less consideration is given to the competitive situation, which is discussed more in Articles 2 and 3, and can be added subsequently as a motive for the development of AFI. Finally, a structurally reinforcing of an awareness of scarcities, environmental damage or a changed market situation can be another factor that implements FDPs and enables the development of AFIs in new markets.

Article 1 (Chapter 2) also highlights different conditions for the emergence of AFIs in industrialized and emerging economies. Accordingly, technological capabilities in the industrialized economies are more pronounced, innovation systems are established, and stronger networking facilitates a flow of necessary information and knowledge. In

emerging markets a necessary mindset is more pronounced due to confrontation with financial shortages and high environmental pollution.

Article 2 (Chapter 3) empirically explores at the company and product level for the development of AFIs. An approach to operationalizing AFI is first developed here to measure environmental and socio-economic benefits of a product that uses these to aggregate overall societal benefits. The resulting distribution of products with environmental and socio-economic benefits suggests a trade-off between these two product types. Products with high environmental benefits are accompanied by higher prices and products with high socio-economic benefits (low product costs) are accompanied by lower environmental benefits. Since this mechanism is predominant only, few products can be identified as AFI. Moreover, it appears that typical design approaches such as concentrating on core functions, and finding effective and efficient solutions for the purpose of use do not have a positive influence on the development of AFI in the context of the studied products. Only the advanced design approaches proposed by Rao (Rao, 2017c, 2017b, 2018, 2019, 2020) that apply advanced materials and technologies have a positive influence, which is demonstrated in the case of environmental benefit. From these findings, two hypothetical development paths can be derived. The Green Technology Development Path and Affordability Development Path.

Article 3 (Chapter 4) investigates the influence of systemic agents on societal product use, building on the conceptual findings of the first Article (Chapter 2). Almost all agents contrarily influence environmental and socio-economic benefits. While the development of green products is promoted by all agents, the cost-side benefits are retarded by most agents. Thus, most agents reinforce the trade-off between the two dimensions. Science and research-related collaborations are exceptional and are considered to positively impact both dimensions. Because key agents such as governments or customers considerably prioritize green products accepting higher prices, most manufacturing products in Germany are positioned on the green technology development path. It is unknown until which point the products will move along this path in their life cycle. The consistency of the product distribution with the influence of the different agents, however, indicates that the systemic framework influences the choice of the development path. Furthermore, the institutional

framework of the German manufacturing sector does not facilitate the combining of both dimensions at this time.

It can be concluded, a key learning that can be drawn from the Articles is that the implementation conditions for frugality in innovation processes must be considered in a regional context. Even if frugal design principles are incorporated into the knowledge base of companies and product development teams, their application can be inhibited by societal conditions. Laws and standards, consumption habits, and a one-sided prioritization of societal goals such as developing a greener economy or improving the quality of life of lower income groups can inhibit the reconciliation of socio-economic and environmental benefits. Implementing of appropriate design approaches must be considered in a broader societal context in which a new awareness of the relationship between environmental and socio-economic benefits is formed.

5.2 Research limitations

For a better classification of this dissertation, it is necessary to discuss limitations of validity. In essence, this dissertation gives a first panorama consisting of theory and empiricism, which have limits of generality.

A limitation of this dissertation is the low theoretical depth, which goes back to the fundamentally almost non-existent theory in this subject area. Since Article 1 (Chapter 2) is the first paper to address AFIs from a societal and economic perspective in a theoretical concept, a deeper consideration was not possible. The main goal of the explorative approach was to create initial hypotheses (Gilson & Goldberg, 2015; Weick, 1989). Accordingly, this research paper is to be considered as a first attempt and the lack of detail needs to be further elaborated in future research. In this context, the theoretical concepts considered, such as the multi-level perspective, innovation systems and institutions, should also be seen as starting points for further research and provide opportunities for deeper linkages with AFI. The presented concept offers a first overview of possible connections and prerequisites for the emergence and implementation of AFI and FDPs.

As already mentioned, the small size of the data set also limits the depth of insights. On the one hand, it limits the scope of possible scientific evaluations as the statistical methods applied are limited to simple evaluations. Transferability to all companies in the manufacturing industry is therefore limited. Although many of the results are

significant enough to draw generalizable conclusions, facets of individual product types and subsectors cannot be identified. On the other hand, the data set only covers companies in the manufacturing sector in Hesse and Lower Saxony. The framework conditions in other German states are unlikely to differ considerably, as laws and standards and customers are likely to be the same in most cases, but this cannot be conclusively assessed due to the lack of comparable data. The same applies to transferability to other industrialized countries, which are likely to be similar to Germany than countries in the emerging markets, but specific differences may also be more pronounced here.

Due to the scope of the questionnaire in connection with the research objective, a broad consideration of additional variables was not possible. This is also related to the questionnaire design, which must consider different levels of knowledge, products and time restrictions into account. Although the variables examined have met the core of the investigation, further indicators would have enabled a broader picture. However, this has only become apparent as a result of this exploratory approach. For a more differentiated picture, it would have been interesting to examine additional agents, indicators that reflect FDPs, and aggregates of socio-economic and environmental benefit. For example, an even more differentiated choice of indicators would have increased the significance of the socio-economic and environmental benefit. From a systemic perspective, the choice of agents could have included financial institutions (Cooke et al., 1997) or the education system (Caniëls & Van den Bosch, 2011). With regard to the FDPs, it would be interesting to consider the Factor of Frugality , as an indicator of the bulkiness of a product (Rao, 2017c, 2018, 2019).

For the current state of research, the research contributions of this dissertation constitute a major advance in terms of theory development and initial empirical findings, despite existing weaknesses.

5.3 Contribution to research areas

This dissertation offers a contribution to different research fields. This mainly includes research on FIs, innovation systems and transition research. It offers contributions from methodological, empirical and theoretical perspectives.

This dissertation comprehensively contributes to the larger research context on FI. A major achievement is the development of a new definitional perspective. Contrary to

previous definitions, the operationalization from Articles 2 (Chapter 3) and 3 (Chapter 4) shapes a different understanding of frugality in which FDPs are not part of the main definition but are seen as key enablers of socio-economic and environmental benefits. This differentiation provides a more objective view and offers new impulses for the research field. In particular, finding a collective definition, whose missing has been strongly criticized (e.g. Hossain, 2021; Stöber et al., 2023), can benefit from it. Based on this, the operationalization approach presented in Article 2 (Chapter 3) offers a new methodological concept that enables to compare AFIs and FIs of different industries and product types on the dimension level. Compared to existing measurement approaches (e.g. Dost et al., 2019; Iqbal et al., 2021, 2020; Rossetto et al., 2017; Santos et al., 2020b), this approach is significantly more complex, but it can better reflect cost and environmental impacts, their interrelatedness, effectiveness of different design approaches, as well as their overall societal benefits. In addition, it also makes it possible to take into account negative externalities that need to be avoided in the context of FI (see Hossain, 2021).

Further contributions are made to theory building by developing a first concept for the societal and systemic emergence framework of AFI whose importance is clarified in Article 3. In research on FI, it is also a first comprehensive concept that examines different emergence factors such as frugal mindset (e.g. Krohn and Herstatt, 2018; Soni and Krishnan, 2014) or cultural background (e.g. Ananthram and Chan, 2019). Similar concepts already exist within frugal ecosystems (e.g. Le et al., 2022; Lei et al., 2021; Sharmelly and Ray, 2018), which, however, focus on market knowledge and emphasize the importance of knowledge and technology less strongly. In this context, especially Articles 2 (Chapter 3) and 3 (Chapter 4) empirically confirm that science and advanced technologies are important ingredients for AFI development and combining cost savings and environmental friendliness, which is widely mentioned by Rao (e.g. 2022, 2021, 2020, 2019, 2018, 2017b, 2013). However, this paper also outlines that classic frugal innovations can become AFIs in the course of life cycle, with the affordability development path. Through subsequent adaptation of design or addition of technologies at high scaling, cost savings can subsequently be supplemented by a higher environmental compatibility. This integrates FI as a possible starting point in the emergence framework of AFI and ties in with existing research on FI that focuses on emerging markets and substantial cost reduction (Gupta, 2012; Weyrauch & Herstatt, 2016; Zeschky et al., 2011).

Smaller contributions are also made to the more established fields of transition research and innovation systems research. From a transition theoretical perspective, this dissertation provides empirical evidence for the existence of product expectations embedded in a socio-technical regime (Fuenfschilling & Truffer, 2014; Geels, 2002) that facilitates the development of green products in the manufacturing sector in Germany. These expectations encompass socio-cognitive, normative and regulative institutions and involve different social and innovation systemic agents. Available literature also suggest that the challenging acceleration of sustainability transition (see Markard et al., 2020) can be supported by AFI. Conceptualizing the AFI supporting innovations system (Chapter 2) is also linked to the current theoretical development on challenge-oriented (Hassink et al., 2022; Tödtling et al., 2021) and mission-oriented innovations systems (Hekkert et al., 2020; Wanzenböck et al., 2020). How they can be applied in context of AFI and how the research fields can benefit from each other should be examined.

In summary, this dissertation expands the field of research on FI and AFI with an economic geographical perspective by developing new methods, empirical findings and linking them to existing theories on the emergence and implementation of innovations. Thus, this dissertation can be seen as a cornerstone for further research on AFI and the formation of green and competitive product characteristics.

5.4 Policy and managerial implications

The research of this dissertation allows to formulate recommendations for action for politics and companies. In doing so, this Chapter builds on the recommendations from the previous Chapters. Since this dissertation mainly deals with companies from industrialized countries, the recommendations are also formulated for companies and decision maker of these countries.

Western companies are caught between complying with green demand in industrialized countries and enabling competitive prices against competitors from Asia. AFIs are one possibility to address this tension and in order to implement them, companies in industrialized countries should enhance their ability to develop low-cost products. If companies in emerging markets expand their capability to develop green and high-quality products while production costs remain low, this capability is a necessity for maintaining their own competitiveness. For example, China is already

one of the largest markets for green technologies (Perruchas et al., 2020) and simultaneously possesses the capability to develop affordable products (Ryans, 2015). The emergence of the ability to develop green and low-cost products outside previously dominant countries may result in a geographical shift of product value creation, with at least a relative loss of wealth for these countries. In this regard, establishing R&D centers in emerging markets, particularly in India, can help integrate frugal design into product development for western companies (Zeschky et al., 2014a, 2011) and provide the opportunity to learn the capability at an early stage and transfer it to R&D centers in home countries (Isaac et al., 2019). In addition, companies should create a business environment that favors the development of green and affordable products early on and that ensures access to suitable materials and technologies. Especially for knowledge-intensive products, it can be more effective to develop frugal innovation in the home market (Altmann & Engberg, 2016).

From a national perspective, the ability to develop AFIs is necessary to maintain social peace while accelerating the transition to a greener economy. This is akin to a political paradigm shift, moving away from the unilateral prioritization of green development and towards a probably more sustainable and effective way to meet long-term climate goals and reconcile ecology and economy. Higher prices for greener products harm the acceptance of change and exclude low income groups from green consumption. Establishing clear and constant framework conditions by political decision makers is necessary. These frameworks should be designed for the long term so that a rethinking from product development to basic research is made possible. Simultaneously, regulations need to be reviewed with regard to their effectiveness and efficiency. Technology and product design standards can make products unnecessarily bulky and must be reviewed on the basis of modern scientific findings and the intended use. In this context, I advocate a technology and design open approach, which also makes the long-term investment of private capital attractive, since R&D is a key enabler of AFI. From a geographical point of view, in addition to the development of a suitable innovation infrastructure, it also makes sense to reduce location-related production costs. The provision of environmentally friendly and low-cost electricity can be seen as a factor in maintaining the competitiveness of a region in future.

Success of corresponding frameworks on an international level may be more promising than on a national level due to a larger integrated market. To resolve the trade-off,

pricing environmentally harmful behavior and the usage of critical raw materials should be foregrounded. Framework conditions that reward environmentally friendly behavior through cost savings are crucial. The EU ETS is a positive example of this (see Borghesi et al., 2015; Calel, 2020; Calel and Dechezleprêtre, 2016; Teixidó et al., 2019), highlighting scarcities and increasing the costs of additional damage. In this context, climate or environmental tariffs could protect the European market from competitors that are not subject to this pricing mechanism.

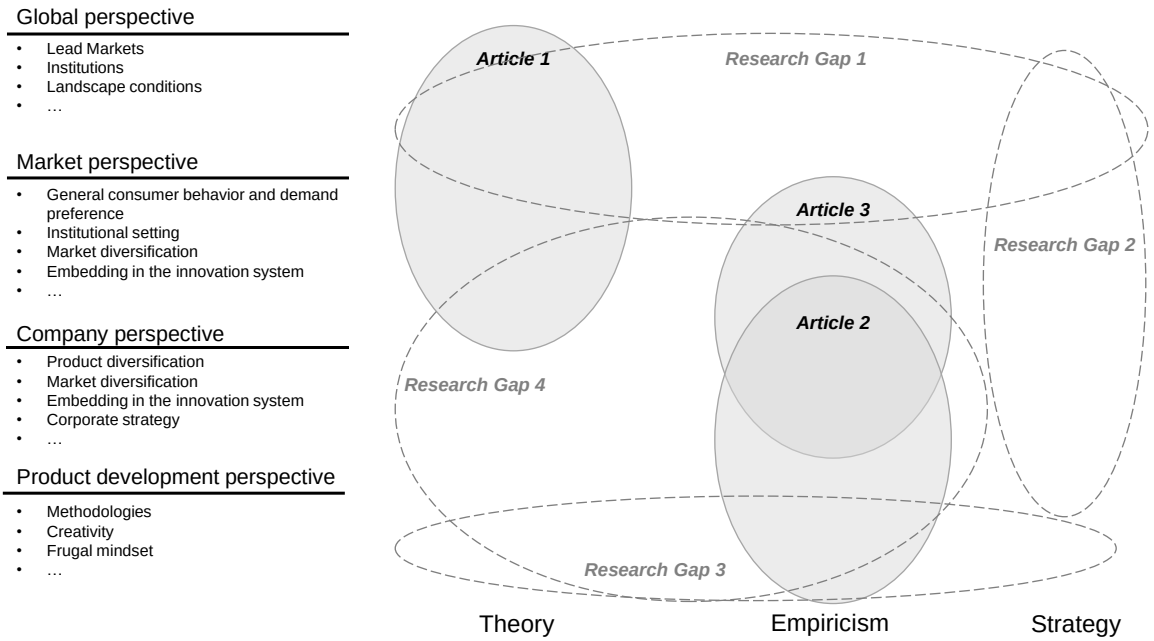
The existing global socio-economic situation suggests that Western economies and companies will face additional pressure of competitors from emerging markets in the future. In order to maintain competitiveness and minimize environmental impacts more comprehensive measures are required, which provide enough material for further dissertations. The complexity and multi-layered nature of this issue requires further research.

5.5 Further research

New research gaps arise from the exploratory research approach. The empirical findings presented in this dissertation only offer first confirmations and raise new questions. The new perspectives of this dissertation can serve as impulses to stimulate the still young research field.

The existing gaps are even more obvious in AFI because of the need of sophisticated technology, knowledge intensive product development and the additional systemic dimension. Transferring theories, empirical findings and strategies from research on FI is difficult and would require further examination. However, findings from other research areas such as environmental innovation perspectives can be transferred. Many open questions can probably be answered deductively by linking and empirically testing the findings of related research. Empirical confirmation and formulating theoretical approaches and strategies for the implementation of AFIs nevertheless still needs extended research. Accordingly, four major research clusters can be identified as gaps in supplementing further evidence of existing research (Figure 13).

Figure 13: Research gaps



Research Gap 1: In the context of AFI, a more global perspective than has been considered so far in the research field of FI is necessary. Since the existing focus on emerging markets is no longer decisive, future research should consider the differences between emerging and industrialized countries. Of particular interest are different framework conditions that facilitate the emergence of AFIs and application of frugal design principles and the identification of institutional bottlenecks in different countries. Factors such as resource scarcity, poverty, innovation capabilities, integration into world trade, climate change, environmental problems, culture, rules and regulations could be research subjects to explain an accumulation of AFIs in certain countries, regions or markets. Detecting potential lead markets (Beise, 2004) can provide information on transition thresholds and facilitate the forecasting of future developments. This analytical framework also includes location-related factors, such as energy mix, energy prices and labor costs, which externally influence product characteristics.

Research Gap 2: General research on FI provides strategies for implementing FDPs in innovation processes, especially in product development and on enterprise-levels. The actual promotion of AFI and FDP from perspectives that go beyond this, including market and global perspective is less investigated. Appropriate action frameworks for political and managerial decision-makers need to be developed. This includes the

evaluation of existing and the development of new strategies, policies, laws, regulations and training of professionals that promote the application of FDP and enable the development of green and competitive products and their establishment in the market.

Research Gap 3: Although Rao's research, especially including the FoF, builds the essential framework to investigate the development of AFI, further research is needed. Thus, further methodologies as well as technologies and materials should be identified that can be classified as FDP. In particular, this is also necessary for the scope of non-physical products such as services, platforms and infrastructure. This could provide a broad pool of knowledge that can be drawn upon in practice. Methods from general FI research such as Constraint-Based Thinking (see Agarwal et al., 2021) could be used for that. In this context also procedures for the analysis of actual product employment and the user behavior are possible, because they facilitate the avoidance of a Simpson paradox or psychological effects and the like. Expanding of the fundus would not only further enhance the potential of the FoF, but also promote a holistic development of AFI which is the foundation for a greener and more inclusive economy.

Research Gap 4: Another research gap is in the company perspective in connection with the product development perspective. While Articles 2 and 3 empirically address these perspectives, this basis is still insufficient and covers only a subset because of its focus on manufacturing and consideration of selected methodologies. The implementation of FDPs in companies in different markets on a large scale is still largely unexplored. Accordingly, it remains to be seen at which levels and structures in the company the decisive levers are to be tightened in order to implement the application of FDP in the long term. Depending on the company structure, industry and product type, it is conceivable that the incentive must come from product development, company management, the market or all levels at the same time. Accordingly, further research which empirically examines these perspectives and offers a possibility for differentiated theory building is needed.

In addition to closing these research gaps, an appropriate research strategy is needed. The divided research field needs a clear research line sharing a uniform definition. This includes FI and terms such as FDP and AFI, which are not self-explanatory. Simultaneously, the interdisciplinary research field needs to become even more interdisciplinary to include more methods and materials with advanced frugal

properties. Moreover, research needs to be grounded in a more comprehensive base of data. Additional case studies, investigating and detecting causalities, can offer further insights, but quantitative empirical findings should be further pre-selected. Company surveys can be an adequate means to this end. In order to generate comprehensive and comparable data sets covering industrialized and emerging economies, linking secondary data and new data collection methods such as web scraping and text mining should be considered.

The research field on FI and AFI has not yet reached a sufficient saturation of knowledge. Regarding the research question "Which framework conditions are necessary for frugality to prevail in innovation processes?", this thesis contributes to the research field by outlining first comprehensive and multi-level framework conditions for the development of AFI and the implementation of frugality in product development processes. AFI offers a high potential to conquer many problems the world is facing. Promoting AFI is therefore absolutely recommendable although connected with a long and challenging way. The advantages are definitely worth this effort.

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Appendix

Appendix A

Questionnaire

A. Company-related Questions

A.I How old is your company?
□ under 1 year
□ 1 to under 3 years
□ 3 to under 5 years
□ 5 to under 10 years
□ 10 years and older
□ No specification

A.II What was your company's turnover in the last completed business year?
□ under 0.5 million Euro
□ 0.5 to under 1 million Euro
□ 1 to under 2 million Euro
□ 2 to under 10 million Euro
□ 10 to under 50 million Euro
□ 50 million Euro and more
□ No specification

A.III What was the percentage of the following key figures in the last completed fiscal year?

	0%	1 to less than 20%	20 to less than 40 %	40 to less than 60 %	60 to less than 80 %	80% and more	No specification
Share of the top-selling product in sales	□	□	□	□	□	□	□
Share of exports in sales	□	□	□	□	□	□	□
Share of exports to emerging markets such as India or China in terms of sales	□	□	□	□	□	□	□

A.IV What was the number of employees in the last completed fiscal year?
□ up to 49
□ 50 up to 249
□ 250 and more
□ No specification

A.III What was the proportion of the following employee groups in the most recently completed fiscal year?

	0%	1 to less than 20%	20 to less than 40 %	40 to less than 60 %	60 to less than 80 %	80% and more	No specification
Share of production-related employees (factory workers, warehouse workers, etc.)	□	□	□	□	□	□	□

Proportion of non-production-related employees (administration, marketing, sales, R&D, etc.)	□	□	□	□	□	□	□
Proportion of R&D-related employees among non-production-related employees	□	□	□	□	□	□	□

B. Product-related Questions

B.I What type of customers do you serve with your top-selling product?
□ Business-to-Customer (B2C)
□ Business-to-Business (B2B)
□ Business-to-Administration (B2A)

B.II In which industry is your top-selling product located?			
□	manufacture of tyres (2211)	□	factory rebuilding of motor vehicle engines (2910)
□	manufacture of rubber hoses and belts and other rubber products (2219)	□	manufacture of bodies for motor vehicles (2920)
□	manufacture of plastic hoses and belts and other plastic products (2220)	□	manufacture of bodies, including cabs for motor vehicles (2920)
□	manufacture of batteries for vehicles (2720)	□	outfitting of all types of motor vehicles, trailers and semi-trailers (2920)
□	manufacture of lighting equipment for motor vehicles (2740)	□	manufacture of trailers and semi-trailers (2920)
□	manufacture of pistons, piston rings and carburetors (2811)	□	manufacture of containers for carriage by one or more modes of transport (2920)
□	manufacture of pumps for motor vehicles and engines (2813)	□	manufacture of electrical parts for motor vehicles (2930)
□	manufacture of agricultural tractors (2821)	□	manufacture of parts and accessories for motor vehicles (2930)
□	manufacture of tractors used in construction or mining (2824)	□	manufacture of motor vehicle electrical equipment (2930)
□	manufacture of off-road dumping trucks (2824)	□	manufacture of diverse parts and accessories for motor vehicles (2930)
□	manufacture of passenger cars (2910)	□	manufacture of parts and accessories of bodies for motor vehicles (2930)
□	manufacture of commercial vehicles (2910)	□	manufacture of car seats (2930)
□	manufacture of buses, trolley-buses and coaches(2910)	□	manufacture of vehicles drawn by animals (3099)
□	manufacture of motor vehicle engines (2910)	□	manufacture of tanks and other military fighting vehicles (3040)
□	manufacture of chassis fitted with engines (2910)	□	maintenance, repair and alteration of motor vehicles (4520)
□	manufacture of other motor vehicles (2910)	□	maintenance, repair and alteration of motor vehicles (4520)
□	ATVs, go-carts and similar including race cars (2910)	□	Other:_____

B.III In which state was the top-selling product significantly developed (optional)?

B.IV Evaluate the features of your top-selling product compared to the average of your competitors' similar products.							
	Much lower			equal			Much higher
Concentration on core functions	□	□	□	□	□	□	□
Focus on comfort and luxury	□	□	□	□	□	□	□
Usability	□	□	□	□	□	□	□

Use of standard components that are not tailored to the product	□	□	□	□	□	□	□
Effective and efficient solutions for the purpose of use	□	□	□	□	□	□	□
Product quality	□	□	□	□	□	□	□
Robustness and durability	□	□	□	□	□	□	□
Purchase price	□	□	□	□	□	□	□
Maintenance and operating costs in use	□	□	□	□	□	□	□
Environmental friendliness of production and use (energy, circular economy, etc.)	□	□	□	□	□	□	□
Raw material requirement of the product in production and use	□	□	□	□	□	□	□
Use of sustainable materials in production and use	□	□	□	□	□	□	□
Application of 4 R (Reduce, Reuse, Recycle, Rethink)	□	□	□	□	□	□	□
Use of advanced technologies	□	□	□	□	□	□	□
Use of advanced materials	□	□	□	□	□	□	□

C. Surroundings Influences

C.I In which direction do customers influence the design of your best-selling product through price expectations, wishes, needs, etc.?

	Extremely reducing			negligible			Extremely reinforcing
Concentration on core functions	□	□	□	□	□	□	□
Focus on comfort and luxury	□	□	□	□	□	□	□
Usability	□	□	□	□	□	□	□
Use of standard components that are not tailored to the product	□	□	□	□	□	□	□
Effective and efficient solutions for the purpose of use	□	□	□	□	□	□	□
Product quality	□	□	□	□	□	□	□
Robustness and durability	□	□	□	□	□	□	□
Purchase price	□	□	□	□	□	□	□
Maintenance and operating costs in use	□	□	□	□	□	□	□
Environmental friendliness of production and use (energy, circular economy, etc.)	□	□	□	□	□	□	□
Raw material requirement of the product in production and use	□	□	□	□	□	□	□
Use of sustainable materials in production and use	□	□	□	□	□	□	□
Application of 4 R (Reduce, Reuse, Recycle, Rethink)	□	□	□	□	□	□	□
Use of advanced technologies	□	□	□	□	□	□	□
Use of advanced materials	□	□	□	□	□	□	□

C.II In which direction do suppliers and cooperation partners influence the design of your top-selling product through capabilities, offers, own ideas, etc.?

	Extremely reducing			negligible			Extremely reinforcing
Concentration on core functions	□	□	□	□	□	□	□
Focus on comfort and luxury	□	□	□	□	□	□	□
Usability	□	□	□	□	□	□	□
Use of standard components that are not tailored to the product	□	□	□	□	□	□	□

Effective and efficient solutions for the purpose of use	□	□	□	□	□	□	□
Product quality	□	□	□	□	□	□	□
Robustness and durability	□	□	□	□	□	□	□
Purchase price	□	□	□	□	□	□	□
Maintenance and operating costs in use	□	□	□	□	□	□	□
Environmental friendliness of production and use (energy, circular economy, etc.)	□	□	□	□	□	□	□
Raw material requirement of the product in production and use	□	□	□	□	□	□	□
Use of sustainable materials in production and use	□	□	□	□	□	□	□
Application of 4 R (Reduce, Reuse, Recycle, Rethink)	□	□	□	□	□	□	□
Use of advanced technologies	□	□	□	□	□	□	□

C.III In which direction do universities and research institutes influence the design of your top-selling product through their knowledge offering, research orientation, etc.?

	Extremely reducing			negligible			Extremely reinforcing
Concentration on core functions	□	□	□	□	□	□	□
Focus on comfort and luxury	□	□	□	□	□	□	□
Usability	□	□	□	□	□	□	□
Use of standard components that are not tailored to the product	□	□	□	□	□	□	□
Effective and efficient solutions for the purpose of use	□	□	□	□	□	□	□
Product quality	□	□	□	□	□	□	□
Robustness and durability	□	□	□	□	□	□	□
Purchase price	□	□	□	□	□	□	□
Maintenance and operating costs in use	□	□	□	□	□	□	□
Environmental friendliness of production and use (energy, circular economy, etc.)	□	□	□	□	□	□	□
Raw material requirement of the product in production and use	□	□	□	□	□	□	□
Use of sustainable materials in production and use	□	□	□	□	□	□	□
Application of 4 R (Reduce, Reuse, Recycle, Rethink)	□	□	□	□	□	□	□
Use of advanced technologies	□	□	□	□	□	□	□
Use of advanced materials	□	□	□	□	□	□	□

C.IV In which direction do the state and trade associations influence the design of your best-selling product through laws, regulations, subsidies, standards, etc.?

	Extremely reducing			negligible			Extremely reinforcing
Concentration on core functions	□	□	□	□	□	□	□
Focus on comfort and luxury	□	□	□	□	□	□	□
Usability	□	□	□	□	□	□	□
Use of standard components that are not tailored to the product	□	□	□	□	□	□	□
Effective and efficient solutions for the purpose of use	□	□	□	□	□	□	□
Product quality	□	□	□	□	□	□	□
Robustness and durability	□	□	□	□	□	□	□
Purchase price	□	□	□	□	□	□	□
Maintenance and operating costs in use	□	□	□	□	□	□	□

Environmental friendliness of production and use (energy, circular economy, etc.)	□	□	□	□	□	□	□
Raw material requirement of the product in production and use	□	□	□	□	□	□	□
Use of sustainable materials in production and use	□	□	□	□	□	□	□
Application of 4 R (Reduce, Reuse, Recycle, Rethink)	□	□	□	□	□	□	□
Use of advanced technologies	□	□	□	□	□	□	□
Use of advanced materials	□	□	□	□	□	□	□

C.V In which direction do owners and investors of your company influence the design of your top-selling product through ideas, motivation, specifications, etc.?

	Extremely reducing			negligible			Extremely reinforcing
Concentration on core functions	□	□	□	□	□	□	□
Focus on comfort and luxury	□	□	□	□	□	□	□
Usability	□	□	□	□	□	□	□
Use of standard components that are not tailored to the product	□	□	□	□	□	□	□
Effective and efficient solutions for the purpose of use	□	□	□	□	□	□	□
Product quality	□	□	□	□	□	□	□
Robustness and durability	□	□	□	□	□	□	□
Purchase price	□	□	□	□	□	□	□
Maintenance and operating costs in use	□	□	□	□	□	□	□
Environmental friendliness of production and use (energy, circular economy, etc.)	□	□	□	□	□	□	□
Raw material requirement of the product in production and use	□	□	□	□	□	□	□
Use of sustainable materials in production and use	□	□	□	□	□	□	□
Application of 4 R (Reduce, Reuse, Recycle, Rethink)	□	□	□	□	□	□	□
Use of advanced technologies	□	□	□	□	□	□	□
Use of advanced materials	□	□	□	□	□	□	□

C.VI In which direction do product developers of your company influence the design of your best-selling product through their ideas, motivation, skills, etc.?

	Extremely reducing			negligible			Extremely reinforcing
Concentration on core functions	□	□	□	□	□	□	□
Focus on comfort and luxury	□	□	□	□	□	□	□
Usability	□	□	□	□	□	□	□
Use of standard components that are not tailored to the product	□	□	□	□	□	□	□
Effective and efficient solutions for the purpose of use	□	□	□	□	□	□	□
Product quality	□	□	□	□	□	□	□
Robustness and durability	□	□	□	□	□	□	□
Purchase price	□	□	□	□	□	□	□
Maintenance and operating costs in use	□	□	□	□	□	□	□
Environmental friendliness of production and use (energy, circular economy, etc.)	□	□	□	□	□	□	□
Raw material requirement of the product in production and use	□	□	□	□	□	□	□

Use of sustainable materials in production and use	□	□	□	□	□	□	□
Application of 4 R (Reduce, Reuse, Recycle, Rethink)	□	□	□	□	□	□	□
Use of advanced technologies	□	□	□	□	□	□	□
Use of advanced materials	□	□	□	□	□	□	□

C.VII In what direction does your company's brand influence the design of the top-selling product through its development, image, etc.?

	Extremely reducing			negli gible			Extremely reinforcin g
Concentration on core functions	□	□	□	□	□	□	□
Focus on comfort and luxury	□	□	□	□	□	□	□
Usability	□	□	□	□	□	□	□
Use of standard components that are not tailored to the product	□	□	□	□	□	□	□
Effective and efficient solutions for the purpose of use	□	□	□	□	□	□	□
Product quality	□	□	□	□	□	□	□
Robustness and durability	□	□	□	□	□	□	□
Purchase price	□	□	□	□	□	□	□
Maintenance and operating costs in use	□	□	□	□	□	□	□
Environmental friendliness of production and use (energy, circular economy, etc.)	□	□	□	□	□	□	□
Raw material requirement of the product in production and use	□	□	□	□	□	□	□
Use of sustainable materials in production and use	□	□	□	□	□	□	□
Application of 4 R (Reduce, Reuse, Recycle, Rethink)	□	□	□	□	□	□	□
Use of advanced technologies	□	□	□	□	□	□	□
Use of advanced materials	□	□	□	□	□	□	□

D. General questions about product development

D.I How high is the percentage of products in your company for which the following characteristics apply compared to products of the competition?

	0%	1 to less than 20%	20 to less than 40%	40 to less than 60 %	60 to less than 80 %	80% and more	No specific ation
Concentration on core functions	□	□	□	□	□	□	□
Low focus on comfort and luxury	□	□	□	□	□	□	□
High usability	□	□	□	□	□	□	□
Use of standard components that are not tailored to the product	□	□	□	□	□	□	□
Effective and efficient solutions for the purpose of use	□	□	□	□	□	□	□
High product quaility	□	□	□	□	□	□	□
High robustness and durability	□	□	□	□	□	□	□
Low purchase price	□	□	□	□	□	□	□
Low maintenance and operating costs in use	□	□	□	□	□	□	□
High environmental friendliness of production and use (energy, circular economy, etc.)	□	□	□	□	□	□	□
Low raw material requirement of the product in production and use	□	□	□	□	□	□	□
Use of sustainable materials in production and use	□	□	□	□	□	□	□

Application of 4 R (Reduce, Reuse, Recycle, Rethink)	□	□	□	□	□	□	□
High use of advanced technologies	□	□	□	□	□	□	□
High use of advanced materials	□	□	□	□	□	□	□

D.II What challenges do you see in the development of resource (raw materials, energy, etc.) and cost-efficient products?

D.III What is necessary to meet these challenges?

D.IV What opportunities (new markets and customer groups, competitiveness, etc.) do you see for your company in the production of resource- (raw materials, energy, etc.) and cost-efficient products?

D.V Through which support programs, measures, etc. are you supported or encouraged in the development of resource (raw materials, energy, etc.) and cost-efficient products?

D.VI In what form do you have a need for support (adaptation of regulations or standards, consulting, digitization, information materials, etc.) in the development of resource- (raw materials, energy, etc.) and cost-efficient products?

Appendix B

Descriptive statistics Article 2

Appendix 1: AFI related product features (Article 2)

Variable	*N*	*Min*	*Max*	*Mean*	*Standard Deviation*
Aggregated Societal Benefit	86	-2.08	1.75	0.07	0.54
Environmental Benefit	86	-2.67	3.00	0.47	0.93
Environmental friendliness of production and use (type of energy, circular economy etc.) (EFPU)	86	-2.00	3.00	0.74	1.17
Use of sustainable materials in production and use (SMPU)	86	-3.00	3.00	0.35	1.05
Application of 4R (reduce, reuse, recycle, rethink) (Ao4R)	86	-3.00	3.00	0.33	1.02
Socio-economic Benefit	86	-2.50	2.00	-0.33	0.86
Selling price (SePr)	86	-3.00	3.00	0.56	1.28
Maintaining and operating cost in use (MOCU)	86	-2.00	3.00	0.09	0.90

The expression reflects the comparison to the average product of the competitors: -3 = much lower application; 0 = equal application; 3 = much higher application

Appendix 2: Product related frugal design applications

Variable	*N*	*Min*	*Max*	*Mean*	*Standard Deviation*
Concentration on Core Functionalities (CoCF)	86	-2.00	3.00	0.70	1.09
Use of Standard Components (UoSC)	86	-3.00	3.00	0.22	1.31
Effective and Efficient Soltutions for the purpose of use (EESP)	86	-2.00	3.00	1.16	1.28
Use of Advanced Materials (UoAM)	86	-2.00	3.00	0.51	0.99
Use of Adcanced Technologies (UoAT)	86	-2.00	3.00	0.80	1.09

The expression reflects the comparison to the average product of the competitors: -3 = much lower application; 0 = equal application; 3 = much higher application

Appendix 3: Moderator related variables

Variable		*N*	*Min*	*Max*	*Mean*	*Standard Deviation*
Aggregated Societal Benefit						
Company Size	Large	31 (36%)	-208	1.75	0.09	0.70
	Medium	38 (44%)	-0.67	1.17	0.11	0.43
	Small	17 (20%)	-1.00	0.75	-0.03	0.44

Export share of sales	60% and more	16 (19%)	-2.08	0.58	-0.14	0.64
	20% to under 60%	22 (27%)	-0.67	1.75	0.11	0.58
	1% to under 20%	31 (38%)	-1.00	1.58	0.13	0.56
	No export	13 (16%)	-0.08	0.50	0.14	0.20
Export to emerging markets	Export	40 (49%)	-2.08	1.75	0.14	0.43
	No export	42 (51%)	-1.00	1.17	0.01	0.64
Environmental Benefit						
Company Size	Large	31 (36%)	-1.67	3.00	0.55	0.99
	Medium	38 (44%)	-2.67	2.33	0.30	0.83
	Small	17 (20%)	-1.33	2.33	0.73	1.01
Export share of sales	60% and more	16 (19%)	-1.67	1.00	0.10	0.59
	20% to under 60%	22 (27%)	-0.33	3.00	0.79	0.99
	1% to under 20%	31 (38%)	-2.67	2.67	0.43	1.04
	No export	13 (16%)	0	2.33	0.51	0.79
Export to emerging markets	Export	40 (49%)	-2.67	3.00	0.45	1.05
	No export	42 (51%)	-1.33	2.33	0.50	0.81
Socio-Economic Benefit						
Company Size	Large	31 (36%)	-2.50	2.00	-0.37	1.03
	Medium	38 (44%)	-1.50	1.50	-0.08	0.67
	Small	17 (20%)	-2.00	1.50	-0.79	0.88
Export share of sales	60% and more	16 (19%)	-2.50	1.00	-0.38	0.99
	20% to under 60%	22 (27%)	-2.00	1.50	-0.57	0.88
	1% to under 20%	31 (38%)	-2.00	2.00	-0.18	0.94
	No export	13 (16%)	-1.50	0.50	-0.23	0.53
Export to emerging markets	Export	40 (49%)	-2.50	1.50	-0.44	0.93
	No export	42 (51%)	-2.00	2.00	-0.23	0.83

The expression reflects the comparison to the average product of the competitors: -3 = much lower application; 0 = equal application; 3 = much higher application

Appendix 4: Industry related variables

Variable	*N*	*Min*	*Max*	*Mean*	*Standard Deviation*
Aggregated Societal Benefit					
Coking plants, Chemicals, Pharmaceuticals and related goods	10 (12%)	-0.50	1.75	0.28	0.68
Electronic and optic, mechanical and related goods	19 (22%)	-0.83	0.83	-0.07	0.45
Food, Beverages, Tabaco and related goods	10 (12%)	-0.42	0.75	0.08	0.33
Rubber, Plastics, Glass, Ceramics and related goods	7 (8%)	-0.50	0.75	0.12	0.44
Wood, Paper, Print and related goods	5 (6%)	-0.25	1.17	0.27	0.53

Textiles, Clothes, Leather and related goods	2 (2%)	0.33	0.50	0.42	0.12
Metal and related goods	13 (15%)	-1.00	1.00	0.10	0.53
Vehicles, related goods and their reparation	6 (7%)	-2.08	0.67	-0.26	0.99
Furniture and other goods	4 (4%)	0	0.42	0.21	0.17
Not specified	10 (12%)	-0.58	1.58	0.05	0.60
Environmental Benefit					
Coking plants, Chemicals, Pharmaceuticals and related goods	10 (12%)	-0.33	3.00	0.67	1.20
Electronic and optic, mechanical and related goods	19 (22%)	-0.33	1.00	0.26	0.38
Food, Beverages, Tabaco and related goods	10 (12%)	0	2.00	0.80	0.88
Rubber, Plastics, Glass, Ceramics and related goods	7 (8%)	0	2.00	0.52	0.77
Wood, Paper, Print and related goods	5 (6%)	0.33	2.33	1.13	0.77
Textiles, Clothes, Leather and related goods	2 (2%)	0.67	2.00	1.33	0.94
Metal and related goods	13 (15%)	-1.33	2.33	0.69	1.05
Vehicles, related goods and their reparation	6 (7%)	-1.67	0	-0.44	0.66
Furniture and other goods	4 (4%)	0	1.00	0.42	0.42
Not specified	10 (12%)	2.67	2.67	0.10	1.31
Socio-Economic Benefit					
Coking plants, Chemicals, Pharmaceuticals and related goods	10 (12%)	-2.00	1.50	-0.10	0.97
Electronic and optic, mechanical and related goods	19 (22%)	-2.00	1.00	-0.39	0.86
Food, Beverages, Tabaco and related goods	10 (12%)	-2.00	0	-0.65	0.71
Rubber, Plastics, Glass, Ceramics and related goods	7 (8%)	-1.50	0.50	-0.29	0.76
Wood, Paper, Print and related goods	5 (6%)	-1.50	0	-0.60	0.65
Textiles, Clothes, Leather and related goods	2 (2%)	-1.00	0	-0.50	0.71
Metal and related goods	13 (15%)	-2.00	1.00	-0.50	0.98
Vehicles, related goods and their reparation	6 (7%)	-2.50	2.00	-0.08	1.53
Furniture and other goods	4 (4%)	-0.50	0.50	0	0.41
Not specified	10 (12%)	-0.50	1.50	0	0.62

The expression reflects the comparison to the average product of the competitors: -3 = much lower application; 0 = equal application; 3 = much higher application

Appendix C

Descriptive statistics Article 3

Appendix 5: AFI related product features (Article 3)

Variable	*N*	*Min*	*Max*	*Mean*	*Standard Deviation*
Aggregated Societal Benefit	63	-2.08	1.75	0.11	0.58
Environmental Benefit	63	-2.67	3.00	0.51	1.02
Environmental friendliness of production and use (type of energy, circular economy etc.) (EFPU)	63	-2.00	3.00	0.79	1.21
Use of sustainable materials in production and use (SMPU)	63	-3.00	3.00	0.41	1.12
Application of 4R (reduce, reuse, recycle, rethink) (Ao4R)	63	-3.00	3.00	0.32	1.09
Socio-economic Benefit	63	-2.50	1.50	-0.29	0.80
Selling price (SePr)	63	-3.00	3.00	0.56	1.23
Maintaining and operating cost in use (MOCU)	63	-2.00	2.00	0.02	0.81

The expression reflects the comparison to the average product of the competitors: -3 = much lower application; 0 = equal application; 3 = much higher application

Appendix 6: Agent influence on AFI related product features (Article 3)

Agent	*N*	*Min*	*Max*	*Mean*	*Standard Deviation*
Aggregated Societal Benefit					
Costumer (C)	63	-2.00	2.08	-0.10	0.68
Supplier and cooperation partner (SCo)	63	-2.50	1.75	-0.16	0.63
Science and research institutes (Sc)	63	-0.50	2.25	0.16	0.45
Government (Gov)	63	-1.50	1.00	0.10	0.44
Shareholder (Sh)	63	-1.50	1.50	0.06	0.52
Product developer (Pd)	63	-1.50	1.50	-0.01	0.56
Brand (B)	63	-1.50	1.50	-0.07	0.53
Environmental Benefit					
Costumer (C)	63	-2.67	2.33	0.50	0.98
Supplier and cooperation partner (SCo)	63	-2.67	2.67	0.38	1.00
Science and research institutes (Sc)	63	-3.00	3.00	0.16	1.07
Government (Gov)	63	-3.00	3.00	0.46	1.29
Shareholder (Sh)	63	-3.00	3.00	0.90	1.35
Product developer (Pd)	63	-3.00	3.00	0.82	1.25
Brand (B)	63	-3.00	3.00	0.74	1.07
Socio-economic Benefit					
Costumer (C)	63	-3.00	2.50	-0.70	1.04
Supplier and cooperation partner (SCo)	63	-3.00	2.00	-0.69	1.05
Science and research institutes (Sc)	63	-2.00	3.00	0.16	0.93

Government (Gov)	63	-3.00	3.00	-0.26	1.17
Shareholder (Sh)	63	-3.00	3.00	-0.78	1.28
Product developer (Pd)	63	-3.00	3.00	-0.83	1.13
Brand (B)	63	-3.00	3.00	-0.88	1.07

The expression reflects the comparison to the average product of the competitors: -3 = extremely reducing; 0 = negligible; 3 = extremely reinforcing

Short Curriculum Vitae

Julian Barnikol is a research associate at the Institute of Economic and Cultural Geography at Gottfried Wilhelm Leibniz Universität Hannover. Born on 13 May 1994 in Giessen, he obtained his higher education entrance qualification at the Gesamtschule Giessen Ost in 2013. After a voluntary year (FSJ) at the Diakoniestation Fernwald-Pohlheim, he studied Geography (B. Sc.), and Economic Geography and Spatial Development Policy (M.Sc.) at the Justus-Liebig University in Giessen with a minor in Economics from 2014. After a semester abroad at Utrecht University in 2018, he graduated with a master's degree in summer 2019. Thereafter, he worked as a project manager for economic and regional research at HA Hessen Agentur in Wiesbaden. In October 2020, he started as a research associate at Leibniz University Hannover in a research project funded by the Lower Saxony Ministry of Science and Culture. He has been enrolled as a doctoral student from October 2022 at the Faculty of Science and successfully defended this dissertation on August 24, 2023.

List of Publications

Peer-reviewed published Articles

Barnikol, J. & Liefner, I. (2022): The prospects of advanced frugal innovations in different economies. Technology in Society, 71, 102081, https://doi.org/10.1016/j.techsoc.2022.102081

Forthcoming Articles

Barnikol, J., Liefner, I., (Forthcoming): Serving society at large: Operationalization and Evidence of (Advanced) Frugal Innovation in Industrialized Economies. Technoligcal Forecasting an Social Change (Under Peer-Review).

Barnikol, J. (Forthcoming): Green and Competitive: Whor influences the development of advanced frugal product characteristics? Technology Analysis & Strategic Management (Submitted).