Guest Editorial: Resource-Constrained Innovation and Frugal Engineering

I. Introduction

MODELS of innovation development usually do not incorporate scarcity of resources as a determinant of the innovation design. Instead, they assume that the necessary resources can be acquired so that a new product or service can be optimally fitted to market preferences. An article by Ray and Ray published in the IEEE Transactions on Engineering Management (IEEE-TEM) in 2010 raised the issue of resource constraints in innovation and how these constraints shape innovation processes and the innovation design [item 1) of the Appendix]. Their article describes the development of an indigenous digital telephone switching system in India, which was developed at a fraction of the research and development (R&D) costs that comparable systems from developed countries required. Around the same time, the terms frugal innovation and frugal engineering were coined for these kinds of resource-constrained innovations [item 2) of the Appendix], [item 3) of the Appendix]. About ten years later, we attempt to look back and ask what progress has been made in the emerging field of frugal engineering management during the previous decade.

The interest in frugal engineering has been boosted dramatically in the last decade with the emergence of the large economies in China and India as burgeoning centers of low-cost innovation. Many innovations in these emerging markets have been described as frugal: being created in a resource-scarce environment and targeted toward an immensely large low-income segment. Some of the now widely known examples from India include the small commercial vehicle, *Tata Ace* [item 4) of the Appendix], the passenger car *Renault Kwid* [item 5) of the Appendix], or the electrocardiogram device *MACi* from the General Electric (GE) stable [item 6) of the Appendix]. In China, GE developed *Vscan*, a portable ultrasound device [item 7) of the Appendix].

Frugal engineering also occurs in system design and on large scale. M-Pesa, a mobile banking application, was developed in cooperation with Vodafone in Kenya and is now widely used [item 8) of the Appendix]. India recently launched its first unmanned mission to Mars, which was successful on its first attempt [item 9) of the Appendix]. The budget available for this was considerably smaller than that of Mars missions already carried out by the USA, Japan, and Russia and in many cases with less success. The costs incurred in the Indian space mission amounted to approximately the production cost of a Boeing aircraft, a fraction of the usual costs for any of the other mars missions.

Radical low-cost innovations have always been a crucial driver in the history of engineering. Ford's Model T, the transistor, and lean manufacturing have radically changed their markets, product architecture, and manufacturing processes. Besides, companies in developed markets, such as Japan have traditionally covered a frugal product segment with target costing [item 10) of the Appendix]. These frugal models, however, are much less visible, as no marketing budget is allocated to them. They do not wear the label "frugal innovation." In developed countries, frugality in engineering and innovation has been primarily attributed to small companies [item 11) of the Appendix] and universities [item 12) of the Appendix] that mostly operate with small development budgets. Still, the emergence of frugal engineering in emerging economies has raised anew the prospect of frugal innovation playing a much more important role in mass markets around the world.

In order to explicate and appraise the prospects of frugality in innovation processes, the essence of frugal engineering needs to be fleshed out, conceptualized, and empirically evaluated. Despite the rising interest in frugal innovation both in research and business practice and notable recent effort [item 13) of the Appendix]–[item 16) of the Appendix], our knowledge about methods, approaches, or procedures that specifically support the systematic development of frugal innovations continues to be insufficient for broader application. It is crucial to identify best practices that achieve development objectives with fewer resources. These best practices are often expected to emerge in developing countries as well as in small companies in developed countries, though large resource-rich companies also target customer segments with high price sensitivity. Cases of frugal innovations offer limited theoretical insights and pathways to theoretically approach the relationships between frugal modes of innovation development and performance and product competitiveness beyond low cost.

We need to widen the theories underlying frugality and open it for cross-thematic appeal. Hence, it seems promising to explore frugal engineering under the more general framework of resource-constrained innovation. On a conceptually more general level, frugal innovation is the outcome of resource and demand constraints. While innovation is rarely created without any constraints, frugal engineering is about operating with much fewer resources than under normal conditions because the

Digital Object Identifier 10.1109/TEM.2020.3040580

resources are not available to the innovator or are deliberately set to meet extreme cost restrictions in the market. Low-income markets, financial limits, undeveloped skill sets, and technical boundaries frame innovation and engineering activities. These constraints influence innovation design. The question of how constraints affect innovation design has only been partially but not systematically assessed.

With this special issue, we attempt to advance the discussion of frugal innovation and engineering. In order to make progress in this field, frugal innovation needs to be embedded in a theoretically precise but also more encompassing framework. The broader term of resource-constrained innovation offers interconnections to other innovation and R&D management domains, such as skill scarcity and training, target costing, credit rationing, time-to-market and even constraints on the market side, and research productivity. The main research question in the field is how constraints affect the innovation design and what are the contingency conditions under which the innovativeness and competitiveness of constraint-induced innovation designs are increased. Within the framework of resource-constrained innovation, we can identify two macro questions: What innovation processes and models fit resource-constrained environments and emerging market needs? What can firms in resource-rich developed economies learn from frugal engineering processes? Or, more specifically, can resource constraints be leveraged in innovation management? We first delve further into defining the issues surrounding resource-constrained innovation.

II. Innovation Under Constraints

Innovation processes usually face a variety of constraints with varying degrees of severity. Constraints are restrictions on the amount or type of inputs (investment, materials, and time) or specific limits of the outputs (cost, exhaust gases, and noise). We define resource constraints very broadly as financial (cash reserves and access to financial markets), physical (tools, raw materials, equipment), human (skills, knowledge, and expertise of individual employees and teams, including their innovative and entrepreneurial skills), informational (such as knowledge about technology, consumer needs, market segments, and competitors), relational (such as relationships between individuals, teams, competitors, suppliers, and consumers), legal (patents, trademarks, and licensees) and organizational (such as controls, routines, and cultures), along with any other resources the firm or the individual has access to [item 17) of the Appendix].

In contrast, resources that are "in excess of the minimum necessary to produce a given level of organizational output" are often referred to as slack resources [item 18) of the Appendix]. While one strand of literature asserts that resource slack is beneficial for innovation, e.g., [item 18) of the Appendix], another strand claims that resource scarcity does not necessarily hamper the innovation outcome but can positively affect the innovation process and lead to distinct innovative solutions. Stokes defines constraints on the innovation process as innovation tools that preclude the search for a design solution in some parts of the design space and steer it to other parts [item 19) of the Appendix]. Basing their arguments on works by Ward [item 20) of the Appendix] and Ward and Dodds [item 21) of the Appendix],

TABLE I
Constraints and Proposed Impact on Innovation Process and Design

Constraint	Examples of Proposed Responses
Resources	
Knowledge	Search for external sources, recombination of existing knowledge (inventive analogies), jugaad
Financial	Risk capital, Reuse of existing solutions, bricolage, outsourcing, standardization over customization
Behavioral (entrepreneurial attitude, motivation)	Capital intensive innovation, incremental innovations based on rules and routines
Material	Bricolage, improvisation, component sharing
Time	Time-efficient solution, modularization
Demand side	
Market size, purchasing power	Frugal innovation
Infrastructure	Insular design
Geographic	Nationally idiosyncratic innovation designs
Regulatory	Compliance innovations, workarounds
Environmental	Eco-friendly innovations Porter/van der Linde Innovations

the conceptual idea of resource-constrained solutions has been explained by Weiss *et al.* [item 22) of the Appendix, p. 199] as follows:

> "[…]when facing a problem, the default approach of people is to implement the first solution that comes to mind […which] is typically based on analogies to a previous solution and therefore fits comfortably with the new problem. Straying from this path of least resistance, however, demands more cognitive effort and creates a higher level of uncertainty in the outcome. Thus, people will stay on the path of least resistance, unless they cannot afford the first solution that comes to mind […]."

Hence, resource constrains pressure developers to deviate from established routines and technologies and raise the likelihood to discover radical or disruptive solutions [item 23) of the Appendix]. Resource scarcity is a varying and dynamic state. It describes a continuum between "insignificant shortage" and "unfulfilled acute need." A slight shortage will not necessarily lead to behavioral changes or radical innovation, but acute distress is comparable to a state of shock that requires immediate action. Severe constraints shape the innovation process as well as the solution or technical design. The term "necessity is the mother of invention" probably belongs to more severe states on the scarcity continuum. But there are surely limits at which constraints are simply discouraging. This relates to the functional form of the relationship between constraints and creativity. In the words of the proponents of slack resources, "there is an inverse U-shaped relationship between slack and innovation in organizations: both too much and too little slack may be detrimental to innovation" [item 18) of the Appendix].

Table I summarizes innovation constraints and their effect on the innovation process and innovation design according to extant literature. We include here both supply as well as demand-side constraints and constraints set by the innovation ecosystem such as government regulation. Most innovation processes certainly operate under at least some financial constraints. Consequently, much attention in recent times has been drawn to the impact of financial constraints on innovation output [item 24) of the Appendix], [item 25) of the Appendix]. Knowledge constraints are genuinely part of all innovation processes since innovation means to discover new knowledge. The role of external information search, recombination of knowledge in different fields, and risk capital has been extensively emphasized in the innovation literature. Jugaad and bricolage are common terms in the frugal innovation field. These constraints affect how innovation designs are wrought. Time constraints can also fundamentally alter the direction of technical progress. When the U.S. President Kennedy announced the plan to send astronauts to the moon "within this decade," he set a time constraint, while more or less giving the National Aeronautics and Space Administration (NASA) virtually unlimited technical resources. NASA realized that in order to fulfill the time constraint, its long-term plan of establishing a space station from which to venture stepwise into outer space needed to be abolished for a more direct route to the moon via a single rocket design [item 26) of the Appendix]. Many design decisions were subsequently derived to fit the bold time constraint. Frugal innovation is predominantly discussed as the outcome of demand restrictions, in particular, low purchasing power, but also skill inadequacy on the user side [item 27) of the Appendix]. Environmental regulations have an explicitly desired effect on innovation design, in that they are aimed at inducing eco-friendlier designs. In a notable article in the Harvard Business Review, Porter and van der Linde proposed in 1995 that certain environmental regulations can also stimulate innovation designs that are more competitive in the market than those that would be developed absent the regulation [item 28) of the Appendix]. A plethora of studies have investigated the Porter hypothesis with contradictory evidence [item 29) of the Appendix].

As mentioned above, the general effect of resource constraints on innovation is also still controversially discussed in the literature [item 18) of the Appendix]. Conventional wisdom and the resource-based view of the firm suggest that resources are essential for innovation and, thus, any constraints on resources reduce innovativeness by restricting research and creative output and restraining would-be innovators. The key contention of the resource-based view is that a firm's innovation process is based essentially on internal resources for managing creativity and on appropriating its knowledge assets. Resource constraints hamper or delay innovation processes and render a constraint-laden innovation design inferior to the design of resource-rich organizations. There is a long tradition in the literature to discuss resource constraints as barriers to innovation [item 24) of the Appendix].

To empirically identify barriers to innovation has, however, proved difficult. Statistical tests based on survey data often find that companies that perceive high levels of barriers to innovation are also more innovative than others [item 24) of the Appendix]. However, this covariance does not imply a causal effect of resource constraints on innovation. The more innovative a company is, the easier they simply run into resource constraints. Furthermore, it has been suggested that resource constraints do not deter companies from innovating altogether but only slow the innovation projects down [item 30) of the Appendix]. One strand of literature maintains that, on the contrary, constraints can spur innovations, at least under certain circumstances. Gibbert and Scranton opine that constraints in the innovation process have been one-sidedly framed as barriers to innovation and that this view fails to appreciate their enabling dimension [item 31) of the Appendix]. Instead, they encourage us to study how past innovations were shaped by constraints. Based on historical studies, we might learn what organizational and behavioral responses various constraints have triggered in the innovation process and what innovation designs and characteristics they have evoked. Gibbert and Scranton illustrate the impact of constraints on the innovation design through several vignettes of the engineering history of jet propulsion engines. The lack of advanced alloys, which could gradually push the limits of heat resistance, led to a more radical and discontinuous solution, the development of an efficient cooling system that eventually progresses to become the dominant design. Emerging environmental constraints triggered radical redesign innovations [item 31) of the Appendix].

Resource scarcity translates into higher prices. The theory of induced innovation, originally suggested by John Hicks in 1932 [item 32) of the Appendix], suggests that innovations are a response to relative increases in factor prices. Changes in factor price relations elicit innovators to invent workarounds. Resources that have become more expensive relative to other inputs have to be reduced or substituted. This substitution process is often impossible without considerable creative changes in the design or the technology used [item 33) of the Appendix]. Since price relations can vary from country to country, innovations often emerge in those countries where resource scarcities emerge first. Historical examples exhibit the importance of factor prices for country-specific technical change [item 34) of the Appendix, p. 199]. For instance, the chemical industry in Germany was induced by the demand for artificial materials to substitute natural resources, since Germany lacked access to raw materials available to competitors from the U.K., the Netherlands, and France in overseas colonies [item 35) of the Appendix, pp. 36–44].

In organizational theory, it has been conjectured that resource-abundant established firms are using more resources than necessary or inappropriate resources because staff feels obliged to use them [item 36) of the Appendix]. Another reproach is that they follow only familiar technological trajectories instead of more creative search paths [item 37) of the Appendix]. The common case for this contention is the remarkable innovativeness of many new firms. Despite being severely resource-constrained on several levels, new firms often dominate radical innovations and constitute an important element in technological revolutions. The "entrepreneurship view" of innovativeness suggests that resource constraints trigger entrepreneurial attitudes in development teams that seek novel opportunities to recombine existing knowledge and create fundamentally new solutions [item 37) of the Appendix]. New small firms are especially innovative in highly competitive environments, in small or demand-constrained markets where resource constraints are the only economic mode to innovate.

The assertions of an association of resource constraints and innovativeness raise the question of applicability in practice. Can managers harness resource constraints to spur innovativeness in their organization and use scarcity as managerial levers to control innovation performance? Artificially constraining resources for innovation projects despite ample company resources and profits can be expected to yield resentments and maybe creative ways to draw added resources to the project [item 25) of the Appendix]. Much more needs to be known about the contextual relationships between constraints and creativity to leverage resource-constrained innovation models for optimal resource allocation in innovation projects. It has to be determined under which conditions resource constraints facilitate innovations, hamper or delay them [item 31) of the Appendix]. Resource constraints can be expected to have different effects under different conditions and in different cultures and industries and concerning different outcome objectives [item 23) of the Appendix]. Weiss *et al.* [item 23) of the Appendix] propose that material constraints raise product novelty but reduce product quality and market outcomes. When radical solutions are sought, constraints spur creativity of innovation staff to conserve scarce resources and search for novel ways to overcome the challenges posed by scarce resources.

Thus, it seems like an overly optimistic outlook to expect resource constraints to automatically lead to superior solutions across the board. This presumption neglects the fact that scarcity of resources can easily discourage employees and elicit negative attitudes toward the work environment and management. Even Asakawa *et al.* [item 33) of the Appendix] admit that "it requires a particular mindset of seeing external constraints as opportunities that may not be valid for all firms." This raises the question of whether specific corporate and national cultures are conducive to frugal innovation processes, as well as the issue of mindsets in frugal engineering.

It should make an important difference whether resources are arbitrarily constrained by management or whether the constraints are forced by external conditions. Artificial resource constraints can lead the staff to question the management's motives or judgment and "fight for more resources" while external adverse conditions can boost motivation and rally the team [item 25) of the Appendix]. An illustrative case for this proposition is provided by Maira's account of how a highly motivated team at India's Tata Motors in the mid-1980s developed its first indigenous and highly successful light commercial vehicle, the *Tata 407*, in the face of existence-threatening regulatory changes dismantling the then-prevailing protection from competition on the one hand, and the restriction on the use of foreign exchange on the other hand [item 38) of the Appendix]. A fitting question to ask, therefore, is what technology management can do under resource constraints to motivate and guide the development team. Weiss *et al.* [item 22) of the Appendix] highlight the important role of setting the right climate and support system with development teams as contingency variable of constraint-laden innovation:

> "[U]nder resource-scarce conditions, it is important that an atmosphere of psychological safety and tolerance of mistakes prevails and that creative thinking is encouraged and supported by providing necessary information and space, not only to cope with financial resource scarcity but to profit from its stimulating effects"

Also, Ray and Ray [item 1) of the Appendix] find that entrepreneurial leadership is a critical success factor for frugal innovation. In this special issue, Pati and Garud look at how organizations can support engineering staff to use the resources at hand [item 39) of the Appendix].

III. Frugal Innovation Design

Frugal innovations have predominantly referred to solutions targeted at price-sensitive customers that include but are not limited to the low-income population in emerging markets. High price sensitivity essentially means that the development of frugal innovation is resource constrained because low target costs limit the project budget. Frugal design is understood as a response to this lack of the "affluent" customer [item 40) of the Appendix]. Market-derived resource constraints are thus included in our definition of constrained-based engineering. Demand constraints are derived not only from a low-income target population, but can also emanate from low benefits of a problem solution that translates into a low willingness-to-pay. Conventionally developed innovations that solve a low-priority problem have often been described as overengineered or victims of the "better mousetrap fallacy" [item 41) of the Appendix]. Frugal engineering can be the solution for this common problem.

The extant literature on frugal innovation has produced some additional hypotheses on the effect of resource constraints on the innovation process and the innovation design. Far from being just stripped-down versions of their high-cost counterparts, frugal innovations have been generally characterized as innovative robust designs, even radical or disruptive innovations, that are built on architectural novelties [item 4) of the Appendix], [item 13) of the Appendix], [item 42) of the Appendix]. However, cases of frugal innovation also emphasize simplification as an essential characteristic, with reduced functionalities, limited features and a general "no-frills" character [item 43) of the Appendix]. This, however, *at times* appears in contradiction to the need to address consumer aspirations in emerging economies [item 44) of the Appendix], [item 45) of the Appendix]. While a cost-effective, no-frills car, such as the *Tata Nano*, has failed commercially in India [item 46) of the Appendix], the *Renault Kwid*, a frugal car, with some bells and whistles (e.g., a stereo receiver) has been more successful in the same market [item 5) of the Appendix]. There are several examples in India's healthcare sector, where functionalities have been rather bundled into a frugal product to reduce total cost of ownership while enabling a greater level of services/functionalities, see, for example, Forus Health [item 47) of the Appendix]. Recently, it has been proposed that an overemphasis on "reduced functionalities" may be counterproductive for the diffusion of frugal innovations. Instead, total cost of ownership in conjunction with perceived utility may be a more important feature of frugal solutions [item 48) of the Appendix].

Asakawa *et al.* assume that frugal innovation processes and products are more self-reliant and more independent from the infrastructure since emerging markets mostly lack many elements of a sophisticated infrastructure [item 33) of the Appendix]. According to Ray and Ray, frugal designs are mostly modular designs [item 1) of the Appendix]. By the end of this decade, however, it became clear that the idea of frugal innovation as a large-scale shift of the cost-performance frontier often calls for an integral design, which requires substantial re-engineering and R&D inputs [item 49) of the Appendix]. Lim and Fujimoto find that in the car industry, frugal innovation requires value engineering of components or materials and "drastic architectural changes from scratch to dramatically reduce all production costs" [item 49) of the Appendix].

Resource and demand constraints are largely a compound. Whereas resource-rich firms tailor innovations for the most demanding customers [item 1) of the Appendix], firms in emerging and developing economies face both resource constraints as well as severe budget restrictions of the mass markets. Ray and Ray characterized the context of emerging markets as high in capital cost and low in labor cost, rending the indigenous innovation processes as labor-intensive and capital-sensitive. For instance, in their study, frugal engineering relied on more manual work instead of automation and software programming, manual testing instead of test equipment, and on repairing of malfunctioning components. While these observations remain valid, more recent studies have shown that successful frugal innovations can emerge from the interplay of digital transformation with unmet customer needs. Studies by Ahuja and Chan [item 50) of the Appendix], Agarwal *et al.* [item 51) of the Appendix], and Tiwari and Kalogerakis [item 52) of the Appendix] have suggested that companies are using digital technologies to circumvent resource constraints and create products that can meet the criteria of "affordable green excellence" to define frugal innovation. Multinational firms can leverage their presence in the emerging economies to tap into local sources of innovation, which seem to be more open to treading unchartered pathways of innovation, motivated by resource constraints.

Still, frugal innovation does not have to be an exclusive domain of emerging economies. A frugal device for early and reliable detection of breast cancer was developed in the United States in a university setting that operates at a fraction of the costs of a conventional mammogram and without radiation exposure [item 53) of the Appendix]. A study of the digital transformation in the wind energy sector suggests that incumbent multinational firms are successfully engaging in the development of solutions leading to affordable green energy [item 54) of the Appendix]. Therefore, firms in developed countries, in spite of their resource-rich surroundings, might be able to implement frugal innovation processes. The Corona pandemic exacerbates financial constraints in developed countries. The resulting financial distress in the economy might enhance the demand for frugal solutions around the world [item 55) of the Appendix]. In this special issue, Walden and Lie present a case of frugal innovation in a highly developed economy [item 12) of the Appendix]. The development of a low-cost firefighter vest responded to budget constraints of a mass market of volunteers instead of the professional market for firefighters. The case shows that collaborating with universities may be a useful approach to develop frugal innovation. Frugal engineering relies on accessing external resources and gaining resources from research units that are intrinsically motivated and thus commit their own resources to a project. Frugal engineering requires new methods and a form of organizational bootstrapping by incentivizing organizational behaviors that are formative of creativity and innovativeness [item 39) of the Appendix], creating a work environment and organizational culture that sustain the motivation of engineers and other project members under severe resource constraints.

IV. Methods in Frugal Engineering

Information on systematic methods and approaches in frugal engineering and for developing frugal innovation is still rather rare. Extant research has recognized the role of value engineering and target costing in the creation of frugal products, such as the Tata Ace or Renault Kwid. Innovation methods, for example, TRIZ and contradiction-oriented innovation strategy, have been linked with frugal engineering [item 13) of the Appendix], [item 56) of the Appendix]. Lehner and Gausemeier [item 15) of the Appendix] have proposed transferring solution patterns from other industrial product or process areas to the development of frugal designs. We now turn to innovation practices and processes that have specifically been suggested as part of the frugal engineering toolbox.

A. Jugaad

Initial literature on frugal innovation often used the Hindi term "jugaad" as synonymous with frugal innovations, see, e.g., [item 57) of the Appendix]. This term refers to smart, cost-efficient improvisations that may be used to circumvent given resource constraints to find an immediate or temporary solution to a pressing problem. Seeking opportunity in adversity, doing more with less, thinking and acting flexibly, maintaining simplicity, including the margins, and following one's heart have been described as "six guiding principles" of jugaad [item 57) of the Appendix]. However, critics have pointed out that jugaad refers to an inherently nonsystematic improvisation process [item 58) of the Appendix], [item 59) of the Appendix]. Jugaad can, therefore, mean taking recourse to inventive analogies from other industries or nature, but it can also mean circumventing regulations and norms in order to achieve a (temporary) workable solution. For this reason, the term is not used or even accepted by many product developers and firms in the formal sector, since jugaad solutions in their original use context in India often refer to substandard quality and as being situated in a gray regulatory zone [item 58) of the Appendix], [item 59) of the Appendix].

B. Bricolage

Some scholars have highlighted the usage of bricolage for creating frugal innovations, see, e.g., [item 40) of the Appendix], [item 60) of the Appendix], and [item 61) of the Appendix]. The term bricolage has been borrowed from anthropology, where it refers to day-to-day practices of dealing with resource constraints [item 62) of the Appendix]. Bricolage can be understood as "[m]aking do with current resources and creating new forms and order from tools and materials at hand" [item 63) of the Appendix], and thus has strong connections with the principles of jugaad. The problems associated with the term jugaad probably also apply to this term as well, because firms do not wish to be perceived as offering a "make-do" solution. However, case studies of frugal innovation have demonstrated that bricolage offers an essential part of the low-cost development process [item 12) of the Appendix].

C. *Inventive Analogies*

Frugal engineering often takes recourse to proven solutions and technologies from other knowledge and use domains, such as other industries or nature [item 64) of the Appendix]. Recombination of existing knowledge applied to solve a new problem offers strong incentives in the form of reduced technological and market uncertainty as well as shortened production time. Product developers are known to have used inventive analogies while creating some of the best-known examples of frugal innovations, e.g., Tata Nano, Tata Ace, and GE's MACi [item 65) of the Appendix].

Recently, two new analytical approaches for studying frugal engineering have been ascertained and exemplified. First, based on action research, a conflict resolution approach to frugal engineering for developing a technical product in industrial settings has been conceptualized (see [item 13) of the Appendix] and [item 66) of the Appendix]). Second, patent analysis of frugal inventions has given rise to schemas that can be followed in frugal engineering projects [item 14) of the Appendix]–[item 16) of the Appendix].

V. Overview of the Compiled Articles

1) The special issue starts with a bibliographic analysis of the most recent literature on frugal innovation by D'Angelo and Magnusson. In "A Bibliometric Map of Intellectual Communities in Frugal Innovation Literature" the authors look at 65 published journal articles about the concept of frugal innovation between 2010 and 2018 and identify four main lenses through which the research community has looked at frugal innovation. The largest group of articles focuses on understanding the strategic mindset, product architecture and design of frugal innovations. Another research domain approaches the issue from the customer side and sees frugal innovation as targeting the bottom-of-the-pyramid and as a means for the alleviation of social problems in emerging markets. A third cluster is interested in the pursuit of sustainability goals and a fourth cluster of articles discussed frugal innovations in specific industries such as in healthcare. The study thus looks back at what has been accomplished in the field of frugal design so far and it reveals that the term frugal innovation has confined the discussion to several niches but lacked the integration and broad interconnections to the main research territories of engineering management. This urgently needs to be the orientation for future research. For instance, D'Angelo and Magnusson suggest that frugal innovation should be connecting with common technology management concepts, such as disruptive innovation.
2) In the paper entitled "Frugal Processes: An Empirical Investigation of the Operations of Resource-Constrained Firms," Knizkov and Arlinghaus attempt to clarify the current state of operations that can be characterized as frugal spanning over the whole supply chain. Their review of the literature and sample of frugal companies serving the bottom-of-the-pyramid market paints a picture of the diversity of frugal processes. They point out that there is a progression of frugality in the production and supply chain in which lean management is an important milestone. In their search for the next Fordian revolution of frugal manufacturing, they present a decentralized, flexible, locally leveraged and engaging procurement, manufacturing and distribution system as a best practice for frugal processes in resource-constrained contexts in developing countries. The article raises the question of whether these principles of frugality are transferable to developed countries and many other questions that demonstrate that still much about frugal processes has to be discovered and clarified.
3) Pati and Garud, in their paper "Role of Feedback on innovative Outcomes in Resource-Constrained Environments," conduct two experiments simulating an innovation project with and without resource constraints. These experiments highlight the role of organizational support in resource-constrained environments and, in particular, the view of "feedback as a resource" of an organization. Under resource constraints organizations can "bootstrap resources" by rallying managerial leadership to provide constructive support of engineers discouraged by the lack of resources. The experimental findings suggest that projects under resource constraints profit from encouragement and means that increase creativity as well as from an organizational culture of providing supportive and constructive feedback. Building an organizational culture often means incentivizing the behaviors that help others being innovative. This article is indeed a contribution to the ongoing quest for best practices in engineering in resource-scarce environments.
4) There have been few operational guidelines or tools for frugal engineering or the development of frugal innovations. Weyrauch *et al.* present such a process approach to frugal innovation. In "The objective–conflict–resolution approach: A Novel Approach for Developing Radical and Frugal Innovation," they start from the proposition that frugal innovations cannot be found as incremental changes, but require radical solutions, which can be reached by focusing on a specific conflict statement among project objectives and customer needs. Frugal innovations are the result of the process of resolution of the most important development objective parameter conflict. The approach culminates in all ideation techniques focusing on this one conflict resolution. Weyrauch *et al.* demonstrate their approach in a real-life engineering project aimed at radical cost reductions of torque limiters.
5) In "Linking R&D Inventors, Social Skills and Bricolage to R&D Performance in Resource-Constrained Environments in Emerging Markets," Garud and Prabhu study the behavioral foundations of R&D personnel working in resource-constrained environments. Starting with the crucial role of bricolage in successfully innovating when few recourses are available, they theorize that the resource construction process is essentially an interpersonal exchange activity. Garud and Prabhu thus discard the lone genius inventor model and show that innovating with scarce resources requires a high level of interpersonal skills, networking and a "collaborative mindset." In particular, Garud and Prabhu argue that effective reuse and

recombination of existing resources involves inventors to access knowledge and other resources from their peers, to negotiate and convince others to exchange resources and to make new connections outside the core team to access diverse resource sets that are best fitted for their R&D projects. Their survey data of 211 R&D personnel confirm that these various interpersonal skills are positively related to R&D outcomes.

6) The article "University–Industry Collaboration in Frugal Innovation through Prototyping: The Case of a Firefighter Cooling Vest" presents a detailed case study of a frugal innovation from an industrialized country. Walden and Lie analyze the real-life project of the development of a cooling vest for volunteer firefighters in which a university provided the product design through intensive prototyping. The authors argue that since university projects are largely very resource-constrained they offer opportunities to study efficient frugal design processes. They suggest that prototyping plays an important role in frugal design because it combines customer needs, manufacturing, and cost efficiency in one process. An iterative prototyping process can serve to concurrently simulate benefits and costs for users and the manufacturing process. Frugal prototyping facilitates a cost-efficient learning process by utilizing bricolage.
7) The last article of the special issue is by Agrawal *et al.* and is titled "Constraint-Based Thinking: A Structured Approach to Develop Frugal Innovations." It uses two case studies of frugal innovations to derive the conceptual idea of constraint-based thinking in the innovation process. The authors suggest that what can be learned from frugal innovations in emerging markets is that concentration of the solution search on any constraints is generally an advantageous approach in innovation. A deep familiarization with the situational internal and external constraints is the key foundation for successful innovations. Based on identified and anticipated constraints, innovation solutions are essentially the result of a mapping between the constraint problem space and the solution space. While not spelling out a constraint-based innovation process in detail, constraint-based thinking is a promising road to developing a more systematic approach to deal with and leverage innovation constraints to boost innovation success.

VI. Future Contributions in Frugal Engineering

The literature on constraint-based engineering has made some progress in the last decade. Yet, much is still unclear and, admittedly, we are still far from being able to flesh out a sophisticated and theory-driven constraint-based engineering and innovation process that could successfully dispel the common view that the creative process must be unconstrained to yield really new solutions. There is some evidence that resource constraints increase the creativity of developers and the novelty of solutions. However, some effects of resource constraints seem rather detrimental to the innovation process. The main idea of frugal engineering, that it leads to not only lower costs but also to a higher innovation performance, has not been unequivocally explained or empirically demonstrated. Additional research should be directed to contingency conditions of frugal design, best practices of frugality in engineering, and detailed managerial decision making in budgeting and leadership. Methodologically, experimental studies under resource constraints seem to be especially beneficial because they control for compounding factors.

Above all, cases of successful frugal innovation demonstrate the need for a normative approach in innovation and engineering management where affordability is not defined solely in monetary terms but also includes societal and environmental affordability. For instance, discourses in affordable green excellence enrich the solution spectrum to fight climate change; frugal innovation in health care and agriculture can be instrumental in fighting poverty and support other millennium development goals.

We hope to have made a modest contribution in this direction with this special issue. We would like to thank all authors for their submissions, revisions, and patience. We would also like to thank all those colleagues, whose submissions could not be considered for this special issue. Special thanks are due to the many reviewers, without whose valuable feedback this special issue would not have been possible. Finally, we would like to thank the professional support of the team at IEEE-TEM.

Rian Beise-Zee, *Guest Editor*
Ritsumeikan Asia Pacific University
Beppu 874-8577, Japan

Cornelius Herstatt, *Guest Editor*
Hamburg University of Technology
21073 Hamburg, Germany

Rajnish Tiwari, *Guest Editor*
Hamburg University of Technology
21073 Hamburg, Germany

Appendix
Related Work

1) P. K. Ray and S. Ray, "Resource-constrained innovation for emerging economies: The case of the Indian telecommunications industry," *IEEE Trans. Eng. Manage.*, vol. 57, no. 1, pp. 144–156, Feb. 2010.
2) N. Radjou, J. Prabhu, and S. Ahuja, "Frugal innovation: Lessons from Carlos Ghosn, CEO, Renault-Nissan," Jul. 2012. [Online]. Available: https://hbr.org/2012/07/frugal-innovation-lessons-from
3) Economist, "First break all the rules: The charms of frugal innovation," *The Economist*, Apr. 17, 2010. [Online]. Available: https://www.economist.com/special-report/2010/04/17/first-break-all-the-rules
4) R. Tiwari and C. Herstatt, "Assessing India's lead market potential for cost-effective innovations," *J. Indian Bus. Res.*, vol. 4, pp. 97–115, 2012.
5) C. Midler, B. Jullien, and Y. Lung, *Rethinking Innovation and Design for Emerging Markets: Inside the Renault Kwid Project*. Boca Raton, FL, USA: CRC Press, 2017.

6) A. Ramdorai and C. Herstatt, “Lessons from low-cost healthcare innovations for the base-of the pyramid markets: How incumbents can systematically create disruptive innovations,” in Lead Market India: Key Elements and Corporate Perspectives for Frugal Innovations, C. Herstatt and R. Tiwari, Eds. Heidelberg, Germany: Springer, 2017, pp. 119–144.
7) J. R. Immelt, V. Govindarajan, and C. Trimble, “How GE is disrupting itself,” *Harvard Bus. Rev.*, vol. 87, pp. 56-65, Oct. 2009.
8) P. Knorringa, I. Peša, A. Leliveld, and C. van Beers, “Frugal Innovation and development: Aides or adversaries,” *Eur. J. Develop. Res.*, vol. 28, pp. 143–153, 2016.
9) A. Lele, *Mission Mars: India’s Quest for the Red Planet*. New Delhi, India: Springer, 2014.
10) T. Hiromoto, “Another hidden edge: Japanese management accounting,” *Harvard Bus. Rev.*, vol. 66, pp. 22–26, Apr. 1988.
11) A. De Massis, D. B. Audretsch, L. Uhlaner, and N. Kammerlander, “Innovation with limited resources: Management lessons from the German Mittelstand,” *J. Product Innov. Manage.*, vol. 35, no. 1, pp. 125–146, 2018.
12) R. Walden and S. Lie, “University-industry collaboration in frugal innovation through prototyping: The case of a firefighter cooling vest,” *IEEE Trans. Eng. Manage.*, to be published, doi: 10.1109/TEM.2020.3032198.
13) T. Weyrauch, *Frugale Innovationen: Eine Untersuchung Der Kriterien Und Des Vorgehens Bei Der Produktentwicklung*. Wiesbaden, Germany: Springer Gabler, 2018.
14) R. Tiwari and S. Bergmann, “Modes and routines of frugal innovation: An examination on the basis of the auto components industry,” in *Handbook of Research on Techno-Entrepreneurial Ecosystems*, F. Therin, F. P. Appio, and H. Yoon, Eds. Cheltenham, U.K.: Edward Elgar, 2019, pp. 46–72.
15) A.-C. Lehner and J. Gausemeier, “A pattern-based approach to the development of frugal innovations,” *Technol. Innov. Manage. Rev.*, vol. 6, no. 3, pp. 13–21, 2016.
16) N. Altgilbers, L. Walter, and M. Moehrle, “Frugal invention candidates as anetcedents of frugal patents—The role of frugal attributes analysed in the medical engineering technology,” *Int. J. Innov. Manage.*, vol. 24, no. 6, 2020, Art. no. 2050082.
17) S. D. Hunt, *A General Theory of Competition: Resources, Competences, Productivity, Economic Growth*. Thousand Oaks, CA, USA: Sage, 1999.
18) N. Nohria and R. Gulati, “Is slack good or bad for innovation?,” *Acad. Manage. J.*, vol. 39, no. 5, pp. 1245–1264, 1996.
19) P. D. Stokes, “A constraint-based model of the creative/innovative process,” *J. Product Innov. Manage.*, vol. 31, pp. 247–258, 2013.
20) T. B. Ward, “Structured imagination: The role of category structure in exemplar generation,” *Cogn. Psychol.*, vol. 27, no. 1, pp. 1–40, 1994.
21) T. B. Ward and R. A. Dodds, “Attribute centrality and imaginative thought,” *Memory Cogn.*, vol. 28, pp. 1387–1397, Dec. 2000.
22) M. Weiss, M. Hoegl, and M. Gibbert, “Making virtue of necessity: The role of team climate for innovation in resource-constrained innovation projects,” *J. Product Innov. Manage.*, vol. 28, no. s1, pp. 196–207, 2011.
23) M. Weiss, M. Hoegl, and M. Gibbert, “How does material resource adequacy affect innovation project performance? A meta-analysis,” *J. Product Innov. Manage.*, vol. 34, no. 6, pp. 842–863, 2017.
24) G. Pellegrino and M. Savona, “No money, no honey? Financial versus knowledge and demand constraints on innovation,” *Res. Policy*, vol. 46, no. 2, pp. 510–521, 2017.
25) M. Hoegl, M. Gibbert, and D. Mazursky, “Financial constraints in innovation projects: When is less more?,” *Res. Policy*, vol. 37, no. 8, pp. 1382–1391, 2008.
26) M. J. Neufeld, Von Braun: Dreamer of Space, Engineer of War. New Yok City, NY, USA: Knopf, 2007.
27) N. Agarwal, J. Oehler, and A. Brem, “Constraint-based thinking: A structured approach to develop frugal innovations,” *IEEE Trans. Eng. Manage.*, to be published.
28) M. E. Porter and C. van der Linde, “Green and competitive: Ending the stalemate,” *Harvard Bus. Rev.*, vol. 73, pp. 120–134, Sep./Oct. 1995.
29) S. Ambec, M. A. Cohen, S. Elgie, and P. Lanoie, “The Porter Hypothesis at 20: Can environmental regulation enhance innovation and competitiveness?,” *Rev. Environ. Econ. Policy*, vol. 7, no. 1, pp. 2–22, 2013.
30) P. D’Este, S. Iammarino, M. Savona, and N. von Tunzelmann, “What hampers innovation? Revealed barriers versus deterring barriers,” *Res. Policy*, vol. 41, no. 2, pp. 482–488, 2012.
31) M. Gibbert and P. Scranton, “Constraints as sources of radical innovation? Insights from jet propulsion development,” *Manage. Org. Hist.*, vol. 4, no. 4, pp. 385–399, 2009.
32) J. R. Hicks, The Theory of Wages. London, U.K.: Macmillan, 1932.
33) K. Asakawa, A. Cuervo-Cazurra, and C. A. Un, “Frugality-based advantage,” *Long Range Planning*, vol. 52, no. 4, 2019, Art. no. 101879.
34) C. Freeman and L. Soete, *The Economics of Industrial Innovation*. Cambridge, MA, USA: MIT Press, 1997.
35) L. G. Franko, The European Multinationals: A Renewed Challenge to American and British Big Business. London, U.K.: Harper & Row, 1976.
36) R. Katila and S. Shane, “When does lack of resources make new firms innovative?,” *Acad. Manage. J.*, vol. 48, no. 5, pp. 814–829, 2005.
37) M. M. Keupp and O. Gassmann, “Resource constraints as triggers of radical innovation: Longitudinal evidence from the manufacturing sector,” *Res. Policy*, vol. 42, no. 8, pp. 1457–1468, 2013.

38) A. Maira, *An Upstart in the Government: Journeys of Change and Learning*. New Delhi, India: Rupa Publications, 2015.
39) R. Pati and N. Garud, "Role of Feedback on innovative outcomes: Moderating role of resource-constrained environments," *IEEE Trans. Eng. Manage.*, to be published, doi: 10.1109/TEM.2020.3015129.
40) M. Pina e Cunha, A. Rego, P. Oliveira, P. Rosado, and N. Habib, "Product innovation in resource-poor environments: Three research streams," *J. Product Innov. Manage.*, vol. 31, no. 2, pp. 202–210, 2014.
41) R. G. Cooper and E. J. Kleinschmidt, "New products: What separates winners from losers?," *J. Product Innov. Manage.*, vol. 4, no. 3, pp. 169–184, 1987.
42) N. Agarwal, M. Grottke, S. Mishra, and A. Brem, "A systematic literature review of constraint-based innovations: State of the art and future perspectives," *IEEE Trans. Eng. Manage.*, vol. 64, no. 1, pp. 1–13, Feb. 2017.
43) T. Weyrauch and C. Herstatt, "What is frugal innovation? Three defining criteria," *J. Frugal Innov.*, vol. 2, 2016, Art. no. 1.
44) A. Maira, "Aspiration alignment: A hidden key to competitive advantage," *J. Bus. Strategy*, vol. 26, no. 6, pp. 12–18, 2005.
45) R. Bijapurkar, *We are Like That Only: Understanding the Logic of Consumer India*. New Delhi, India: Penguin, 2009.
46) K. B. Nielsen and H. Wilhite, "The rise and fall of the 'people's car': Middle-class aspirations, status and mobile symbolism in 'New India,'" *Contemporary South Asia*, vol. 23, no. 4, pp. 371–387, 2015.
47) Forus Health, "3nethra classic: Digital non-mydriatic fundus camera," 2019. [Online]. Available: https://www.forushealth.com/3nethra-classic.html
48) R. Tiwari, "Frugal innovations: An inquiry into causes, effects and pathways of affordable excellence," Habilitation thesis, Inst. Technol. Innov. Manage., Hamburg Univ. Technol., Hamburg, Germany, 2019.
49) C. Lim and T. Fujimoto, "Frugal innovation and design changes expanding the cost-performance frontier: A schumpeterian approach," *Res. Policy*, vol. 48, no. 4, pp. 1016–1029, 2019.
50) S. Ahuja and Y. E. Chan, "Digital innovation: A frugal ecosystem perspective," presented at the 37th Int. Conf. Inf. Syst., Dublin, Ireland, 2016.
51) N. Agarwal, K. Chung, and A. Brem, "New technologies for frugal innovation," in Frugal Innovation: A Cross Global Research Companion, A. J. McMurray and G. De Waal, Eds. Abingdon, U.K.: Routledge, 2020, pp. 137–149.
52) R. Tiwari and K. Kalogerakis, "What enables frugal innovation? An examination of innovation pathways in India's auto component industry," in Managing Innovation in a Global and Digital World: Meeting Societal Challenges and Enhancing Competitiveness, R. Tiwari and S. Buse, Eds. Wiesbaden, Germany: Springer Gabler, 2020, pp. 253–268.
53) S. Cousins, "A new way to detect breast cancer," Aug. 29, 2018. [Online]. Available: https://www.nytimes.com/2018/08/28/opinion/detect-breast-cancer-developing-countries-asia.html
54) R. Tiwari, "Digital transformation as enabler of affordable green excellence: An investigation of frugal innovations in the wind energy sector," in Frugal Innovation and its Implementation: Leveraging Constraints for Driving Innovations on a Global Scale, N. Agarwal and A. Brem, Eds. New York, NY, USA: Springer.
55) C. Herstatt and R. Tiwari, "Opportunities of frugality in the post-Corona era," *Int. J. Technol. Manage.*, vol. 83, pp. 15–33, 2020.
56) O. Mayer and T. Bertoncelli, "TRIZ-assisted frugal innovation," in *New Opportunities for Innovation Breakthroughs for Developing Countries and Emerging Economies*, R. Benmoussa, R. De Guio, S. Dubois, and S. Koziołek, Eds. Cham, Switzerland: Springer, 2019, pp. 81–92.
57) N. Radjou, J. Prabhu, and S. Ahuja, Jugaad Innovation: Think Frugal, Be Flexible, Generate Breakthrough Growth. San Francisco, CA, USA: Jossey-Bass, 2012.
58) R. T. Krishnan, From Jugaad to Systematic Innovation: The Challenge for India. Bangalore, India: Utpreraka Foundation, 2010.
59) T. Birtchnell, "Jugaad as systemic risk and disruptive innovation in India," *Contemporary South Asia*, vol. 19, no. 4, pp. 357–372, 2011.
60) A. Gurca and M. N. Ravishankar, "A bricolage perspective on technological innovation in emerging markets," *IEEE Trans. Eng. Manage.*, vol. 63, no. 1, pp. 53–66, Feb. 2016.
61) A. K. Nair, R. Tiwari, and S. Buse, "Emerging patterns of grassroots innovations: Results of a conceptual study based on selected cases from India," in Lead Market India: Key Elements and Corporate Perspectives for Frugal Innovations, C. Herstatt and R. Tiwari, Eds. Heidelberg, Germany: Springer, 2017, pp. 65–95.
62) C. Levi-Strauss, *The Savage Mind*. Chicago, IL, USA: Univ. Chicago Press, 1966.
63) T. Baker, A. S. Miner, and D. T. Eesley, "Improvising firms: Bricolage, retrospective interpretation and improvisational competencies in the founding process," *Res. Policy*, vol. 32, no. 2, pp. 255–276, 2003.
64) K. Kalogerakis, C. Lüthje, and C. Herstatt, "Developing innovations based on analogies: Experience from design and engineering consultants," *J. Product Innov. Manage.*, vol. 27, pp. 418–436, 2010.
65) R. Tiwari, K. Kalogerakis, and C. Herstatt, "Frugal innovation and analogies: Some propositions for product development in emerging economies," presented at the R&D Manage. Conf., 2014.
66) T. Weyrauch, C. Herstatt, and F. Tietze, "The objective–conflict–resolution approach: A novel approach for developing radical and frugal innovation," *IEEE Trans. Eng. Manage.*, to be published, doi: 10.1109/TEM.2020.3000924.

Rian Beise-Zee received the master's degree in engineering, in 1994 and the doctoral degree in economics from the Technical University of Berlin, Berlin, Germany, in 2001.

He is currently a Professor with the College of International Management, Ritsumeikan Asia Pacific University (APU), Beppu, Japan. He was an Associate Dean with the Graduate School of Management for five years, and since 2020, he has been the Dean of International Cooperation and Research. He teaches product development strategy and service management. He joined APU in 2012. He was previously an Associate Professor with the Asian Institute of Technology, Klong Luang, Thailand (2006–2012) and a Research Fellow with Kobe University, Kobe, Japan, and City University of Hong Kong, Hong Kong. Before his university career, he was a Senior Researcher with the Center for European Economic Research, Mannheim, Germany (1994–2003). He has authored or coauthored more than 20 articles in peer-reviewed journals such as *Research Policy, Small Business Economics, Ecological Economics,* and *Organization Studies*.

Dr. Beise-Zee is a Member of the Editorial Board of the IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT.

Cornelius Herstatt received the master's degree in business and economics from the Universities of Cologne and Zurich, in 1987 and the doctorate degree in business management from the University of Zurich in 1991.

He is a leading German researcher and university professor for innovation management. He holds the Chair in the Technology and Innovation Management, Hamburg University of Technology (TUHH), Hamburg, Germany, and has cofounded the Center for Frugal Innovation, TUHH. In recent times, he has been particularly interested in so-called "frugal innovations," which often emerge in the context of developing countries and are a driving force for inclusive innovation. Another focus is his research on social innovations in developing countries, supporting social cohesion among others. His research is internationally oriented and focuses on Asia and Europe. He researches and publishes together with international colleagues and institutions. He is an author and editor of 25 books on innovation research and several hundred publications in German, English, and Japanese. He has held visiting professorships at Australian, Japanese, and American universities and is an alumnus of the Japan Society for the Promotion of Science, the German Institute for Japanese Studies, the East-West Center (Hawaii) and Templeton College (Oxford). He is an advisor to small and large companies, policymakers, and NGOs around the world.

Rajnish Tiwari received the master's degree in business management from the University of Hamburg in Germany, in 2005 and the doctorate degree in field of technology and innovation management from the Hamburg University of Technology, Germany, in 2013.

He is currently a Senior Research Fellow with the Institute for Technology and Innovation Management, Hamburg University of Technology (TUHH), Hamburg, Germany. He leads the research program Global Innovation and has cofounded the Center for Frugal Innovation, TUHH. He has advised Germany's Federal Ministry of Education and Research concerning "new global innovation pathways" and has led projects to investigate potentials of "affordable excellence" in countries, such as India, Germany, Japan, and Austria in various sectors including food processing, automotive, and renewable energies. His current research revolves around digital transformation as enabler of affordable green excellence. He is an alumnus of the Japan Society for Promotion of Science and has been a Visiting Fellow at several universities in Australia, India, Japan, and the USA, besides being an Adjunct Faculty with the Manipal Institute of Technology in India.