

Review



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Frugal innovation: doing more with less for more

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The global economy will face significant challenges over the next few decades. On the one hand, it must meet the needs of 7 billion consumers (growing to 9 billion by 2050), including the currently unmet basic needs of large numbers in developing countries in areas such as food, energy, housing and health. On the other hand, it must achieve this growth without exceeding the resources available on the planet or causing environmental devastation. This paper argues that such change is possible through a systemic shift to a frugal economy that involves radical, frugal innovation across sectors. Such a transformation will involve the participation of large and small firms, consumers and governments alike. The paper introduces the notion of frugal innovation—the creation of faster, better and cheaper solutions for more people that employ minimal resources—and discusses strategies and examples of such change already taking place in core sectors like manufacturing, food, automotive and energy in developing and developed economies. It also outlines the role of the interaction between large and small firms as well as between firms and consumers in making change possible, as well as the role of governments in driving change where market mechanisms alone will not suffice.

This article is part of the themed issue 'Material demand reduction'.

1. Introduction

Over four billion people around the globe—more than half the world's population—live outside the formal economy and face unmet needs in basic areas such as food, energy, sanitation, financial services, healthcare and education [1]. Most of these people live in the developing countries of Asia, Africa and Latin America,

where poor infrastructure and incomplete institutions exacerbate their condition. For many decades these large populations were left to the mercy of their often negligent governments or to the largesse of aid from developed economies. In recent years, however, firms of various kinds—large and small, domestic and multinational, public and private sector—have begun to develop market-based solutions to meet the needs of these populations [2–6]. These solutions typically: (i) address issues of affordability and resource constraint by being frugal and making effective use of limited resources and (ii) involve excluded groups, both as users as well as producers and distributors of products and services, thereby augmenting incomes and driving development [3,7,8].

Meanwhile, in the developed world, declining real incomes and reduced government spending, accompanied by greater concerns about the environment, have made consumers both *value* and *values* conscious. Specifically, Western consumers have become more and more used to getting by with less [9] or on smaller budgets [10]. At the same time, they have become more demanding about what types of companies they buy from or work for. For instance, a series of recent reports (see [11]) finds that 66% of Western consumers are willing to ‘pay extra for products and services that come from companies who are committed to positive social and environmental impact’ (up from 55% in 2014 and 50% in 2013), while 67% ‘prefer to work for socially responsible companies’ [12]. Further, more and more people in the West are now empowered to do with limited resources what only large firms or governments could do in the past [13]. Ubiquitous tools and technologies such as smart phones, cloud computing, three-dimensional printers, crowdfunding and social media have given rise to frugal grassroots innovation and entrepreneurship exemplified by the lean start-up and maker movements [14–16] and the sharing economy [17]. Thus, frugal innovation is increasingly a growing phenomenon also in the developed world [7].

This paper will examine the phenomenon of frugal innovation—the creation of faster, better and cheaper solutions that employ minimal resources—and argue that it holds the key to meeting global needs creatively while addressing the problems of resource constraint that stalk the planet (see [3,7,13]). It will discuss what frugal innovation is and how it relates to similar concepts in areas such as economics and engineering, as well as in specific sub-areas such as eco-innovation, sustainable innovation, and sustainable consumption and production. The paper will go on to examine both demand and supply side aspects of frugal innovation. It will then highlight examples across sectors of such innovation by entrepreneurs, emerging market firms and multinationals in the North and South, and discuss the challenges and opportunities for small and large firms alike. The paper will end with a discussion of how a systemic transition to a frugal economy is likely to take place as well as a discussion of the boundaries conditions and limitations of the ideas introduced in the paper.

2. The nature of the problem and this paper’s thesis

From an economic standpoint, the last 200 years have marked a radical break for humankind and the planet from all that came before. Rapid industrialization (especially in the West) has raised hundreds of millions of people out of the drudgery of agricultural labour into the relative ease of manufacturing and service-based work, with the fruits of this transition being increased leisure, more secure access to food and livelihoods, and longer, healthier lifespans [18].

Industrialization, and the market-based model it is founded on, now promises to deliver similar benefits in the emerging economies of Asia, Africa and Latin America. Indeed, in China alone, a manufacturing-based, export-led model of growth has lifted over 300 million people out of poverty into relative wealth over the last two decades or so [19]. India hopes to follow suit, and large parts of Africa are not far behind.

Such growth is to be welcomed as it helps meet the fundamental needs of people in large parts of the globe. However, it also poses a resource and environmental challenge on a global scale. Put simply, if India, China and the African economies were to employ the same industrial model that

the West used in its own development, this would bankrupt the planet. As Paul Polman, CEO of Unilever puts it: if the emerging world is to catch-up with the West, in the way that the West became prosperous, we will need the resources of two planets [13].

So the problem this paper wishes to address is: how can economies around the world meet the needs of 7 billion people (growing to 9 billion by 2050) without bankrupting the planet or causing environmental collapse? Growth over the next few decades would, therefore, have to happen in a radically different, resource aware and environmentally sustainable way. This paper will examine what that model of growth would need to look like. It will argue that what is needed is a new way to innovate: an innovation model that is essentially frugal and focuses on meeting the needs of more people with radically fewer resources. It will argue that such frugal innovation cannot be incremental, but rather must be radical and systemic. In essence, the problem then becomes one of change—organizational, sectoral, systemic and global—involving many different players: firms, consumers and governments.

Firms are, of course, a major engine of innovation. Accordingly, much of the paper will focus both on the large corporations that dominate their sectors across the globe as well as new ventures that hope to unseat these incumbents through innovation. Large corporations account for most of the goods and services that enter the world economy and so also account for the use of most of the resources that are needed to produce and deliver these goods and services. For instance, the 500 largest companies in the world together account for 28% of world gross domestic product (GDP) and produce directly or indirectly (through their energy use) about 13% of global greenhouse gas emissions (see [20]). Large firms also have the know-how and financial and marketing muscle needed to scale new solutions. However, because their success is dependent on existing technologies and systems, they tend to prefer incremental over radical innovation [21,22]. While incremental change can deliver resource efficiencies over time, this is unlikely to be sufficient to bring about the radical change that is needed to ensure sustainable growth over the next few decades. New ventures, on the other hand, are not committed to the status quo. Indeed, their route to success depends on doing things in radically new ways [21,22]. Accordingly, this paper will examine the question of resource-constrained growth by looking at the competitive interaction of large corporations and new ventures across sectors around the world [23]. In some cases, this will involve head-on competition between the old and the new, while in others it may involve incumbents working together with new ventures, especially where their respective capabilities are complementary [23,24]. For instance, in areas such as autonomous vehicles and smart homes, there is a strong case for relatively new, data smart firms such as Google working with traditional incumbents such as GM and GE, respectively.

In a market-based system, firms are only one half of the equation. Consumers are the important other half. Consumers around the world are increasingly aware of environmental issues; many even care deeply about promoting more sustainable consumption practices [25]. Nevertheless, the onus is often on companies to nudge or shove consumers towards more sustainable consumption practices [26]. Accordingly, this paper will examine demand-side trends and the link between the actions of firms and those of consumers in driving sustainable growth.

Further, in many cases, market dynamics alone will not drive systemic change. For instance, in many sectors, firms may wait for consumer preference or behaviour to change before introducing innovations. And consumers, for their part, might wait for firms to introduce innovations that require them to change their patterns of consumption. Alternatively, competition from start-ups might be too weak or slow to force incumbents to change their existing, resource-depleting business models. In such cases, governments will have to play a role, introducing legislation or incentives that break the deadlock, increase competition and hasten systemic change.

Finally, this paper will look at frugal innovation across the globe, in both developed and emerging economies. In developed economies (relative to developing economies), better institutions, higher levels of human capital, and greater financial and technological resources, all potentially work together to enable a smoother and quicker transition from a wasteful, unsustainable economic system to a more frugal, sustainable one. On the down-side, however,

developed economies (and the firms that operate in them) are typically committed to older industrial models and technologies (i.e. legacy systems) that, because they are more deeply embedded, are harder to shake off. In emerging markets, on the other hand, firms and economies have the potential opportunity to leap-frog to entirely new clean technologies and industrial systems [27]. This paper will examine the dynamics of how firms in developed versus developing economies might benefit in different ways from frugal innovation to become sustainable.

3. Definitions and conceptual background

(a) Innovation

Innovation is the successful commercial exploitation of new ideas [28–30]. As such, innovation (and hence the management of innovation) involves identifying, developing and exploiting new ideas to generate value.

Innovation can be of many types and typologies of innovation abound [31]. This paper will focus on the three main types most relevant to resource reduction: product/service, process and business model innovation.

Product innovation involves the commercial introduction of a tangible, physical offering that is new to customers [31–33]. Examples include smartphones and electric vehicles. Service innovation involves the commercial introduction of an intangible service that is new to customers [34,35]. Examples include cryptocurrencies such as Bitcoin and streaming video services such as Netflix.

Process innovation involves the use of a new approach to creating or commercializing products or services [31,33,34,36]. Examples include the assembly line in manufacturing and the use of electronic platforms to manage large infrastructure projects in construction.

Business model innovation involves systemic change to both the offering itself and the process by which it is made and delivered [34,37,38]. An example is online retailing which both delivers more value to consumers (a far greater assortment, customer reviews, recommendations based on big data) while dramatically reducing operating infrastructure and costs such as inventory, warehousing and retail outlets.

All three types of innovation can be either radical or incremental in scope. Radical innovations typically employ substantially new technology and offer substantially higher customer or user benefits relative to existing products, services or processes [39]. Incremental innovations, by contrast, involve minor changes to technology or minor improvements in customer benefits. While incremental innovations can cumulatively help reduce resource use, it is likely that only radical innovations will truly solve the acute problems that the planet faces over the next few decades.

Finally, some radical innovations can prove disruptive to existing companies, products, technologies and customers [22]. These innovations typically introduce a different set of features, performance and price attributes relative to existing products, and initially underperform products available to mainstream customers. However, a different customer segment may value the new attributes and, over time, the new product's attributes may improve to a sufficient level to attract mainstream customers, eventually taking over the market [40]. Examples include PCs over mainframes and workstations, and mobile phones over landlines.

(b) Frugal innovation

Frugal innovation can be defined as an attempt to maximize the ratio of value to resources [13]. Value could be for customers, shareholders or society more generally. Resources could be energy, capital or time. Thus, frugal innovation is the ability to 'do better with less resources for more people', i.e. to create significantly more value while minimizing the use of resources (see [7,41] for a detailed historical and conceptual discussion of the concept of 'frugal innovation'; see also [8]).

The frugal approach to innovation is disruptive. It requires companies to focus on simultaneously maximizing value while minimizing the use of resources.

It should be noted that related terms exist in the literature that address similar phenomena to those that the term ‘frugal innovation’ covers (see [7,41,42]). These include *jugaad* innovation [3,4], Gandhian innovation [8], cost innovation [42], reverse innovation [43] and inclusive innovation [44,45]. However, the consensus seems to be that the term frugal innovation best captures the range of phenomena that these other terms aim to capture [7]. As such, this paper uses the term ‘frugal innovation’ throughout.

Further, frugal innovation bears some similarities to related notions in business concerning socially responsible innovation such as shared value (see [46]). Like shared value, frugal innovation is concerned with doing better not only for the firm but also other stakeholders that firms engage with (e.g. communities). However, frugal innovation is a broader concept than shared value. First, frugal innovation is about generating greater value for whoever the firm chooses to generate this value for: consumers, shareholders or society more generally. Second, frugal innovation is greatly concerned about the means employed to generate greater value, specifically the *resources* employed to generate value. Shared value tends to ignore this part of the equation. Specifically, frugal innovation looks at how greater value can be created even while reducing the resources needed to generate this value, whether those resources be financial or natural resources or time.

4. How does frugal innovation compare to related notions of efficiency in economics and engineering?

Frugal innovation shares an important general similarity with the engineering and economics definitions of efficiency: all three are broadly concerned with maximizing outputs (e.g. quantity produced) while minimizing inputs (e.g. material resources).

However, there are some subtle differences between frugal innovation and the other two notions of efficiency. Take the engineering definition of Allwood *et al.* [47] first. As Aidt & Low [48] point out, the engineering definition only considers the role of material resources as an input; it ignores the role of other inputs such as labour. Further, the engineering definition does not, therefore, account for trade-offs that firms must make between the two inputs of labour and materials given their respective prices. As a result, while the engineering and economic notions of efficiency might sometimes coincide, they are not necessarily the same. Frugal innovation is therefore closer to the economics definition of efficiency. Specifically, like the economics definition, frugal innovation does consider the role of multiple inputs: financial resources (capital) and human resources (labour) as well as material resources (e.g. energy) and time.

The frugal innovation approach, however, also differs from the economics notion of efficiency in several ways. First, it considers time also as an input. The economics definition does not factor in time. Second, unlike the economist’s approach which considers consumer preferences as a given, the frugal innovation approach recognizes that consumer preferences are somewhat pliable and can be influenced by a firm’s actions (such as prices, promotion, advertising, etc.).

There are also some important methodological differences between the three approaches. The economics approach is deductive and top-down in nature. The economist makes some (often heroic) assumptions about the nature of firms and consumers and then deduces how resources are allocated in the economy. Thus, while attempting to be descriptive and predictive, the approach is really normative in nature. It in fact outlines how the world should be ideally (if all the assumptions were fulfilled). The engineering approach, by contrast, is less utopian (as it does not make as many heroic assumptions), but is nevertheless normative as it is concerned with what firms ought to do, not what they actually do.

By contrast, frugal innovation is a descriptive notion based on and drawn from the actual practices of firms. Specifically, it relies on empirically grounded, bottom-up induction and

attempts to describe how firms that are so inclined might attempt to generate more value in terms of outputs using fewer resources (inputs). It recognizes that firms' actual practices are messy and suboptimal in essence. However, it also leaves room for firms to aspire towards and achieve more optimal (or less suboptimal) outcomes. Further, there is the implication of how this greater value can be generated for more people; thus, there is also an implication of scale and including otherwise excluded groups. As a result, the frugal innovation approach means firms do not have to be optimally profitable: they are allowed to 'leave money on the table' because of lack of motivation, ability or opportunity. However, the approach also acknowledges that firms *try* to be profitable. Thus, an underlying assumption of the frugal innovation approach is that firms will choose to adopt it because it can help increase profits. This can happen in three ways: (i) by reducing costs (because of reduced inputs), (ii) by increasing price (because of increased value), or (iii) by increasing sales (by reaching more people).

Finally, the methodological differences between frugal innovation on the one hand, and the engineering and economics definitions of efficiency on the other, result in an important distinction in their respective approaches to policy. The engineering and economics approaches, as they are deductive and top-down in nature, tend to look first to government intervention, specifically through taxation and regulation, to bring about systemic change. The frugal innovation approach, on the other hand, being bottom-up, is mainly concerned with how market and competitive pressures might on their own first result in systemic change. More specifically, the frugal innovation approach focuses on the role of business in bringing about systemic change, specifically the competitive process between large incumbents and agile start-ups in their drive to meet changing consumer needs and preferences. It is only when market failure is known to happen that the frugal innovation approach turns to government policy and regulation to bring about systemic change.

5. How does frugal innovation compare with related ideas in eco-innovation, sustainable design and sustainable consumption and production?

There is a rich and growing literature on innovation in the context of sustainability. For instance, the literature on sustainable consumption examines changes on the demand side, including the possibility of prosperity without growth and how consumer well being might improve with reduced consumption (see [49–56]). Meanwhile, the literature on sustainable production examines changes on the supply side including how firms can make more eco-informed material choice and improve the eco-efficiency of production [47,57–60]. Finally, the areas of eco-innovation [61–64] and sustainable innovation [65–69] examine how firms can innovate to be more environmentally sustainable.

Frugal innovation shares many similarities in both scope and spirit with these disparate areas of prior research. For instance, it shares the focus on models of growth and well being that are environmentally and socially sustainable, and recognizes that such growth requires systemic innovation to take occur. Further, it recognizes that such models of sustainable growth require both supply (production) and demand (consumption) side change to occur. The frugal innovation approach, however, differs from these other approaches in three important ways. First, it is more holistic in nature. Namely, it considers simultaneously the role of demand and supply in bringing about systemic change. Given that frugal innovation is a ratio of the value generated for consumers and society to the resources used to generate such value, it simultaneously takes into account how resources can and should be used to bring services to more people globally. Second, the frugal innovation approach is global in its perspective. Specifically, it explicitly examines the role of both developing and developed countries in bringing about systemic change. Indeed, the initial impetus for the study of frugal innovation began in severely resource-constrained developing countries that nevertheless face growing demand for basic services from their large, relatively poor populations. It is only recently that such pressures to do more with less for more have also spread to developed countries. Finally, the frugal innovation approach focuses

on the role of business in bringing about systemic change, specifically the competitive process between large incumbents and agile start-ups in their drive to meet changing consumer needs and preferences. Specifically, the approach focuses on how market pressures on the one hand drive firms to respond to the needs of ever larger numbers of consumers worldwide by delivering products and services of greater value while resource constraints and competitive forces, on the other hand, drive them to constantly find ways to deliver this value by using fewer resources (including time).

6. Supply side drivers of frugal innovation

Companies face constant competitive pressure to improve the value they deliver to customers. This competitive pressure also drives them to constantly improve the efficiency with which they make and deliver their offerings to consumers. In recent years, growing resource scarcity and volatility has added to the pressure on companies to adopt frugal innovation. Several companies have now placed, or are in the process of placing, environmental sustainability at the heart of their business models [13,70]. An outstanding example is Unilever and its 2010 Sustainable Living Plan. Other firms that have similarly ambitious plans include M&S (Plan A) and Kingfisher (Net Positive Plan).

In order to achieve these ambitious objectives, companies have had to adopt the frugal innovation approach across a range of their activities, including (i) how they source raw materials and manage their factories and supply chains, (ii) how they design and package their products, and (iii) how they engage with consumers to make them more environmentally conscious in their consumption behaviour. I use the case of Unilever to elucidate how large companies are going about making these changes and the challenges they face along the way.

In November 2010, Unilever's CEO Paul Polman launched the Unilever Sustainable Living Plan. The plan was inherently frugal in its approach: it aimed to double sales (i.e. increase value) while halving the company's environmental impact (i.e. decrease the use of resources) by 2020. Specifically, the plan had three pillars: deliver more value to more people (e.g. improve health and hygiene for over a billion new consumers especially in emerging markets); halve its environmental footprint; and enhance livelihoods, including those of 500 000 smallholder farmers and distributors that it works with worldwide. While the time limit on the plan has subsequently been extended to 2030, its goals remain ambitious: the firm serves two billion consumers (that it has plans to double) and its operations include over 250 factories and 450 warehouses in nearly 100 countries around the globe (see [13]).

(a) Sourcing raw materials and managing factories and supply chains

Unilever plans to reduce the environmental footprint of its supply chain in two ways. First, by sourcing all its agricultural raw materials sustainably. This in turn involves reducing or eliminating deforestation and ensuring that the smallholder farmers the company sources from pursue sustainable agricultural practices. The firm has made some progress towards this goal. By the end of 2015, it reported that 60% of its agricultural raw materials were being sustainably sourced (see [71]).

Second, it aims to make manufacturing and distribution more eco-efficient and reduce greenhouse gas, water and waste impacts across its entire supply chain. For instance, Unilever has a very ambitious target of becoming 'carbon positive' in all its operations by 2030. This includes sourcing 100% of all energy it uses from renewable sources. It has made progress on this score. It reduced CO₂ emissions from energy by 39% per tonne of production relative to 2008 [71]. Other improvements include reduced water abstraction by 37% per tonne of production and reduced waste sent for disposal by 97% per tonne of production (relative to 2008) [71]. By early 2016, over 600 Unilever sites worldwide had achieved zero non-hazardous waste to landfill. Overall, these changes have avoided costs of over €600 million since 2008.

(b) Design and packaging of products

Its deodorant business poses a particular challenge for Unilever. Aerosols in deodorant cans contribute to greenhouse gas emissions and the aluminium in the cans requires a lot of energy to manufacture. To address this issue, Unilever set out to produce more concentrated cans. The company has also followed a concentration approach to product design in its detergents business where ‘three times concentrates’ have replaced what Unilever used to call their ‘dilutes’ business where packs were twice as large and twice as heavy.

Concentration in product design and formulation has other environmental and cost benefits. Smaller pack sizes reduce distribution costs; this in turn has enabled Unilever to cut its truck fleet by 20%. Thus, frugal innovation has resulted in less transport, less packaging, and less waste to landfills, and much of these savings can be passed on to consumers. As a consequence of these changes, by 2016, the waste associated with the disposal of Unilever products has reduced by 29% (relative to 2010) [71].

(c) Engaging with consumers to make them more environmentally conscious in their consumption behaviour

The power balance between firms and consumers in a market economy is a potentially paradoxical one. While consumers are collectively powerful, they are individually powerless to bring about systemic change. Firms, especially large ones, on the other hand, have considerable market power; and yet, even the largest firms cannot force consumers to make major changes in their behaviour [72]. Nevertheless, firms have multiple tools at their disposal that they can use to nudge consumers to change [26]. A major such tool is the product itself that firms sell to consumers.

Unilever aims to help consumers use less water, less energy and recycle more through how it designs its products and markets its brands. Its aim is to appeal to more consumers with sustainable brands. For instance, when it began to explore making concentrated aerosol deodorants, the company began by asking consumers how much their decisions were influenced by environmental concerns. They found that consumers were unwilling to trade performance for sustainability and were unwilling to pay more. Unilever’s challenge then became how to provide better performance in a more sustainable way. When the firm developed concentrated aerosols they managed to put the contents of a 150 ml can into a 75 ml can. But this presented a new problem: consumers felt they were now getting less value. To counter this, Unilever introduced a new valve and a radically reengineered actuator that maintained performance. The concentrates strategy has been rolled out across multiple brands including Lynx, Dove, Axe, Rexona and Vaseline, and the firm aims to spread this know-how across all its businesses.

7. Demand-side drivers of frugal innovation

(a) Prosumers and the frugal economy

A significant demand-side trend, especially in Western economies, is the rise of so-called prosumers, consumers who are no longer passive recipients of goods and services from companies but who are actively involved in the economic process [73]. These prosumers are, in turn, driving at least two movements which hold significance for a new more frugal economy: the maker movement and the sharing economy [13].

(b) The sharing economy

Increasingly, consumers are empowered to directly trade, share or swap spare assets with each other, often on online and smartphone platforms designed to facilitate these transactions in a seamless, convenient and efficient way. Thus, prosumers can now ‘share’ spare rooms or homes

through Airbnb, cars or rides through BlaBlaCar, parking space through ParkatmyHouse, and cash through peer-to-peer lending and crowd-funding sites such as Zopa and Kickstarter.

Such ‘collaborative consumption’ [17] services are asset light, scale fast and make better use of existing resources (rather than requiring the use of new resources). They are therefore inherently frugal in nature and highly disruptive of many traditional industries and their business models. For instance, Airbnb now rents more rooms per year than Hilton’s entire global chain does. BlaBlaCar, the car-sharing service, transports more people in Western Europe than Eurostar, the high-speed train service, does.

The shift towards collaborative consumption and sharing mirrors another related trend in consumption: namely, a move away from the ownership and consumption of physical things towards the consumption of intangible experiences [74]. This preference for experiences, especially among younger consumers, is in turn a reflection of the increasing growth of the service sector over manufacturing, especially in developed economies. This so-called ‘servitization’ of industry [75] holds out the prospect of a more resource light economy in the future: one in which value is created less through the use of physical resources and more through the creation of non-physical, psychological or social experiences.

(c) The maker movement

Consumers around the world, but especially in the West, are increasingly empowered to do better with less. Thanks to increasingly ubiquitous tools such as three-dimensional printers, cheap sensors and computers, and maker spaces such as Tech Shops or FabLabs that offer such tools and communities of like-minded people, small groups of prosumers can now innovate in ways that only large companies or the government could in the twentieth century.

These tools and spaces, along with crowd-funding sites and social media, are spurring a ground-up, start-up revolution in software and hardware, whereby ‘prosumers’ develop and then commercialize do-it-yourself (DIY), frugal solutions to local needs that can then quickly find global application. For instance, the mobile messaging service WhatsApp was developed by three former employees of Yahoo! with little money and in a short period of time. The app now does 30 billion messages a day, 10 billion more than all the telecom companies do together.

The maker movement has spawned events such as Maker Faires that celebrate the DIY ingenuity of ordinary citizens. Mayors around the world are now vying with one another to host these fairs. Even Barack Obama hosted a Maker Faire in the White House in 2014 partly driven by the belief that ‘Today’s Do-It-Yourself is tomorrow’s Made in America’.

8. Sectoral developments

(a) Manufacturing

Many recent developments in manufacturing promise a global shift towards a more frugal industrial system. I outline some of these developments below.

(i) Modular and continuous manufacturing

Firms in sectors like automobiles, pharmaceuticals and energy are moving from a system of a few large, centralized plants with many dedicated production lines (all of which add energy and cost) to multiple, smaller but nimbler plants with versatile production capabilities. For instance, all Volkswagen factories now use a process called Modularer Querbaukasten (MQB) which enables multiple models to be made using the same assembly line [76]. Nissan, Toyota and others are following suit [13,77]).

Meanwhile, Novartis and MIT have developed a self-contained, ultra-compact production unit that can manufacture drugs 10 times faster than giant purpose-built plants can (see [78,79]). These factories can be reconfigured when necessary to make small, customized batches of drugs. GSK is

also committed to such ‘continuous manufacturing’: almost half of the company’s current drugs portfolio could soon be made this way. The benefits would include a significant reduction in process time, cost, carbon footprint and speed [13].

In the energy sector, electricity used to be generated in a few central mega-units and transmitted over hundreds of miles to customers’ homes and offices. Increasingly, however, the sector is moving to decentralized systems where smaller units generate electricity closer to points of consumption [80]. In 2014, for instance, GE Distributed Power began to supply distributed power systems to utilities, cities and large manufacturers. Investment in distributed power technologies is expected to grow from \$150 billion in 2012 to over \$200 billion in 2020 [13].

(ii) Additive manufacturing

In contrast with subtractive manufacturing, in which a larger block of material, usually metal, is reduced or hammered into shape, additive manufacturing uses three-dimensional printers to add several successive layers of a material until the product is made [81]. Additive processes use less energy and waste less, and can mass customize at far lower cost (see [82]). Three-dimensional printers now use an increasing range of materials from plastic and stainless steel to ceramics and glass, and can print complex products such as prosthetic limbs, concept cars, houses, electronic gadgets, orthodontic appliances and even spare parts for fighter aircraft [13].

Based on over 20 years of research, GE now has a global additive manufacturing team of 600 engineers across 21 sites and is committed to developing parts and components using such techniques across its business lines. Examples of three-dimensional printed parts include fuel nozzles for jet engines and ultrasound transducers for medical devices (see [83]).

(iii) Industrial symbiosis

Companies around the world are increasingly pursuing cooperative approaches to manufacturing that are mutually beneficial. Called ‘industrial symbiosis’ or ‘industrial ecology’ such approaches involve the geographical co-location of traditionally separate industries that exchange materials, water, energy and other by-products between their manufacturing facilities (see [84–87]). The basis of industrial symbiosis is therefore the synergistic sharing of resources to improve individual and collective efficiency and reduce waste.

Denmark has been a pioneer in the practice of industrial symbiosis (see [88,89]). In 1972, the Nordic giant Statoil began supplying excess gas from its refineries to Gyproc, a local gypsum producer, to dry the plasterboard produced in Gyproc’s ovens. That first foray has resulted, four decades later, in the Kalundborg Industrial Eco-Park: a web of nine co-located factories that exchange waste, energy, water and information in their manufacturing processes [88,89]. Members of the ecosystem collectively save 3 million cubic metres of water through re-use and recycling and have reduced their annual CO₂ emissions by 240 000 tons, resulting in financial savings of \$15 million a year and accumulated savings of over \$300 million (see [90,91]). Other annual environmental benefits of the Kalundborg network include savings of liquid sulfur (20 000 tons), biomass (319 000 m³), yeast slurry (42 500 tons), SO₂ emissions (53 tons), NO_x emissions (89 tons) and gypsum (170 000 tons) (see [91]).

The success of Kalundborg has inspired other governments to follow suit. In 2003, the UK government set up the National Industrial Symbiosis Programme (NISP) to encourage firms to exchange water, energy and waste materials across their businesses [92,93]. Since its birth, the NISP’s nearly 15 000 members have together redirected nearly 50 million tons of waste away from landfills and reduced the UK’s emissions by over 40 million tons. The NISP model is now being replicated in several countries around the world [94].

(b) Agriculture and food

The Earth’s human population is expected to grow from 7 billion today to 9.5 billion by 2075. Hunger and malnutrition are already a major problem around the world. In addition to feeding

the existing 7 billion, the world will have to find ways to feed 2.5 billion more people over the next few decades [95]. This is a major problem given the limited and diminishing supply of arable land around the world. Further, growing food requires other scarce resources such as water, energy and fertilizer, many of which are carbon positive.

One relatively simple yet frugal way to address the problem of feeding 7 to 9 billion people sustainably is through the reduction of food waste [72]. It is estimated that between a third and a half of all food produced worldwide is wasted. This equates to 1.2 to 2 billion tons of waste per year out of 4 billion tons produced [95]. Interestingly, almost equal proportions of food are wasted in the developed as in the developing world. However, this waste occurs in different parts of the supply chain and for different reasons. In the developing world, waste mostly occurs upstream in the supply chain, from so-called 'farm to fork', because of poor or non-existent storage and cold chain facilities. Thus, in India, the Food and Agriculture Organization estimates that 40% of vegetables and fruit rot before they reach the consumer [96]. In the developed world, waste mostly occurs downstream, nearer the point of consumption. In the United States and Europe, for instance, consumers are estimated to throw away up to half the food they purchase [72].

The type of frugal innovation needed to solve the problem of food waste is likely to be different in the developing versus the developed world. In the developing world, the state can play a key role in this shift. First, it can improve critical infrastructure such as roads and railways to improve the speed with which food can be transported from farms to cities. Second, it can create the incentives for large, consolidated retailers to enter the market and provide the investment needed to develop storage, processing and cold chain facilities. Countries such as China have led the way in this, and provide a roadmap for others to follow [97].

In the developed world, meanwhile, a large part of the problem of food waste is due to the prevailing business model in the sector. The current business model, driven by large retailers who play a central role in the supply chain, favours over-production and supply of food [72]. Retailers prefer to have an oversupply of food in their stores and promote consumption (with, for instance, 'buy one get one free' offers) rather than risk having empty shelves that might drive customers to switch to competitors' retail outlets. This model, combined with the challenges of forecasting and matching food demand with supply, the over-zealous adherence to high cosmetic standards for fruit and vegetables, and the improper use of sell by and use by dates results in large amounts of food waste and the concomitant waste of embedded resources such as water and energy [72].

In the developed world, therefore, addressing food waste requires systemic change that starts with retailers. Specifically, an efficient circular economy in the food industry requires retailers to closely coordinate their actions with other players in the supply chain such as farmers and consumers. Retailers will need to adopt long-term relationships with farmers (as opposed to transactional, auction based approaches) even as they engage with customers and nudge them towards more responsible consumption of food. This change in the business models of traditional retailers is increasingly been driven by the entry of intrinsically frugal online only retailers (such as Ocado in the UK and Amazon). Further consumer activism as well as regulatory pressures are also hastening this process of change in food retailing.

(c) Automotive and mobility

The automobile industry forms the backbone of many economies, driving jobs in manufacturing and stimulating economic growth both directly and indirectly. However, vehicles of all forms also contribute greatly to carbon emissions and pollution. Frugal innovation in this sector therefore assumes critical importance. The use of new, lighter materials, for instance, can reduce the weight of cars thus increasing their fuel efficiency (see [47,57,60]). And new manufacturing processes can help boost the productivity of the industry while making it more environmentally friendly. But two breakthrough innovations in particular hold out the promise of a radical, systemic transformation of the sector: electric cars and autonomous vehicles.

(i) Electric cars and autonomous vehicles

Electric vehicles are potentially a systemic solution to the many environmental problems posed by fossil fuel-based automobiles. Two major obstacles have stood in the way of the development and adoption of electric vehicles. First, most large incumbent automotive companies are invested in maintaining the current business model built around fossil fuels. For these firms to shift to an electric vehicle based business model involves significant risk and organizational commitment [98]. Second, car buyers have been reluctant to switch to electric vehicles because of the cost of batteries, the lack of charging infrastructure and the limited driving range of current models [99]. Again, such a switch involves risk on their part and a considerable commitment to environmental over cost and convenience considerations.

The first problem—namely the inertia of incumbent companies—has to some extent been mitigated by the entry into the sector of non-incumbent start-ups such as Tesla Motors [98]. Recognizing that the take-off of electric cars requires systemic change and collective technological efforts around driving range and battery technology, Tesla has taken steps like making its patents available to others to build on as well as investing in lithium-ion battery manufacturing at scale. In this way, Tesla also hopes to address the second problem of consumer inertia.

Meanwhile, autonomous vehicles are increasingly a technological reality thanks to breakthroughs in the use of data and GPS technology [100]. Again, the charge is being led by non-automotive, databased firms such as Google (although incumbents like Ford are now following suit). Autonomous vehicles offer the possibility of moving to a more frugal and efficient system of car use, one in which car sharing becomes much more efficient and convenient, reducing the carbon footprint and energy needs of the sector. The obstacle to the adoption of autonomous vehicles is mainly around regulation. Given the newness of the technology and the legal and other issues around safety and liability, governments will play a key role in how this sector develops. Interesting developments on this front include the UK's newly created Centre for Connected and Autonomous Vehicles. A joint venture between the Department for Transport and the Department of Business, Innovation and Skills, the Centre is charged with working with software and automotive firms to trial ways in which autonomous vehicles can improve urban transport in the decades to come.

(ii) Car-sharing trends

A major development on the demand side has been the increasing preference among (especially) young, urban consumers for car-access over car-ownership models. Zipcar (and its equivalents from around the world) allow such consumers to gain access to 'pay as you go' car-sharing services in a convenient and affordable way that is also better for the local community and the environment [101–103]. Such car-sharing models are matched by ride sharing businesses such as Uber (which is mainly intracity) and BlaBlaCar (which is mainly intercity). Even incumbent automotive firms such as BMW are experimenting with car-sharing clubs as a way to tap into the trend. And city governments are not far behind. Helsinki, for instance, has the ambition of making car ownership unnecessary by transforming the city's public transport network into 'a comprehensive, point-to-point mobility on demand system by 2025' [104]. The idea is to allow citizens to be able to 'purchase mobility in real time, straight from their smartphones' and make this system so 'cheap, flexible and well-coordinated' that it is competitive with car ownership on cost, convenience and ease of use [104]. Such a system would build on developments in autonomous driving, car-sharing models and the move to electric vehicles.

(d) Energy

Energy is the foundation stone on which economies are built. Moving to a carbon-free, renewable energy platform is at the heart of all attempts to move to a global frugal economy. While much progress has been made in improving solar and wind technologies, and many countries now derive a large proportion of their energy needs from these sources, barriers to such a

transformation remain. A key barrier concerns storage: renewable sources such as solar and wind are intermittent by nature and require cheap and efficient means of storing energy when it can be generated (such as during the day or when the wind is blowing) to be used when it is needed (i.e. at peak times such as during late evenings) (see [105]). Governments are partnering with academics and companies around the world to overcome this barrier. The US Energy Department, for instance, is funding research at MIT, Stanford and Harvard, as well as Lawrence Livermore and Oak Ridge laboratories, into new storage technologies that can reduce costs by as much as 80% in a bid to provide renewable energy at \$100 per kilowatt hour [106].

A second obstacle is the need for new types of infrastructure to support the transition to clean energy, in particular a clean energy grid that reaches even remote regions of countries. This is particularly the case in developing countries where the last mile problem makes it too costly for resource-constrained governments to invest the financial and other resources needed to develop such an extensive grid [107]. A related problem in developing countries is that, lacking access to a clean energy grid, large numbers of people are forced to resort to unhealthy (for humans and the environment) sources of energy such as low quality biomass and kerosene or diesel for lighting, cooking and industrial needs. In this context, new off-grid solutions, often involving cleaner sources of energy such as solar, micro-hydro and cleaner biomass, are becoming increasingly widespread and attractive.

(i) Off-grid solar lighting solutions

The last decade has seen a rapid proliferation of solar lighting solutions across the developing world. A key challenge that these solutions face in driving adoption is consumer financing. Many of the target consumers of such solutions are unbanked and so do not have access to bank loans or digital payments services. However, the spread of mobile phones and of SMS-based mobile payments solutions such as M-Pesa are helping overcome this barrier too. Companies like M-Kopa, for instance, install solar-lighting solutions in huts in rural Kenya and allow customers to pay off the up-front cost of the equipment in instalments through micro-payments on the M-Pesa platform [108].

In Bangladesh, where many rural communities do not have access to the electricity grid, kerosene and diesel are often used to meet lighting and energy needs. In 2003, the state-owned Infrastructure Development Company Limited (IDCOL) began a programme to scale solar home solutions in the country. At that time, only 7000 households (out of 27 million) had access to such systems [109]. Backed by the World Bank, the Global Environment Facility, the US Agency for International Development, the UK Department for International Development and others, IDCOL provided flexible refinancing, grant support and technical assistance to its commercialization partners and end users. In total, 58 solar home solution providers joined the programme; these providers extended credit to households at an affordable price and provided after-sales and maintenance. Over a decade of exponential growth for such solutions has resulted in more than 3.7 million systems installed by 2015, serving about 17 million people (around 11 per cent of the total population of Bangladesh). By 2017, IDCOL aims to facilitate 6 million installations, generating 220 megawatts of electricity for communities that were previously unserved [109].

Solar lighting, while undoubtedly beneficial, is not enough. As Ashok Choudhury, Deputy Director, Odisha Renewable Energy Development Agency in Odisha, India puts it: 'When you ask villagers what's their priority for getting electricity they always prioritize livelihood. Number two is entertainment and number three is illumination. We always do the third priority first, so we don't make much headway because our programme can't support livelihoods' (see [110]).

Enter Ashok Das and SunMoksha: a smart grid technology that allows a village's entire electrical infrastructure to be monitored remotely. This in turn addresses the difficulty of monitoring and maintaining larger off-grid systems that can do more than light homes. In January 2016, Chhotkei in Orissa became India's first smart village powered by SunMoksha's Smart NanoGrid technology [110]. Power is provided by a 30 kW solar plant and meters and sensors

collect data on energy usage and system health. These data are fed into SunMoksha's cloud-based monitoring system. Supply and demand are remotely managed. In this way, the firm can schedule power-hungry irrigation pumping and microenterprise activity such as food packaging and storing cold drinks. Wi-Fi hotspots give villagers access to a local intranet via a mobile app to view their consumption, pay bills and register complaints. If users exceed their allowance, they can be shut off to avoid overloading the grid. Faults can be spotted remotely and villagers trained in basic repairs can then be sent to fix them. On-going expenses are covered by usage-based subscriptions paid to a village committee that maintains the grid.

Experiments such as this suggest that developing countries might well be able to leap-frog the process of full clean electrification of their economies without requiring the time and resources that the developed world needed to achieve such electrification.

9. Discussion and limitations

(a) Power and motivation: a model of how systemic global transition to a frugal economy might occur

A major objective of this paper is to shed light on the role of business in bringing about a systemic global transition to a frugal economy. Specifically, the aim is to show how the competitive process between large incumbents and agile start-ups in their drive to meet changing consumer preferences can bring about such change. Thus, the focus is on how market pressures, on the one hand, drive firms to respond to the needs of ever larger numbers of consumers worldwide by delivering products and services of greater value while, on the other hand, resource constraints and competitive forces drive them to constantly find ways to deliver this value by using fewer resources including time.

A second, and related, theme of this paper concerns the shifts in power that are challenging traditional business models worldwide. The first major shift in power is the rise of consumers relative to producers. In particular, the paper highlights the emergence of prosumers: consumers who are no longer passive recipients of goods and services from companies but are actively involved in the economic process [73]. These prosumers are not only concerned with consuming in a more socially and environmentally responsible way, but they are also empowered to actually do so through access to tools and technologies that enable them to choose who they buy from and how they consume (see [17]).

The second major shift in power is the rise of new ventures relative to large incumbents. Ubiquitous tools and technologies, such as smart phones, cloud computing, three-dimensional printers, crowdfunding and social media, have given rise to frugal grassroots entrepreneurship exemplified by the lean start-up and maker movements [14–16]. These frugal companies, some of which like Google, Amazon and Facebook have grown in the space of a decade to become behemoths, now threaten the dominance of far older incumbents across sectors.

A third major shift in power is the rise of emerging markets relative to developed economies. Emerging markets now not only account for many more consumers, but they also account for the greater proportion of world GDP, both in absolute and growth terms. As a result, multinational firms are increasingly turning their attention to the opportunities that emerging markets offer.

Taken together, these three shifts in power are placing increasing pressure on large, incumbent firms (most of whom originate in developed economies) to innovate faster, better and cheaper. On the one hand, these firms are under pressure to deliver more affordable goods and services to more consumers worldwide. On the other hand, they face increasing scarcity of raw materials and volatility in their prices. Further, they are under competitive pressure from lean and agile start-ups whose data-driven, asset-light business models are fundamentally frugal from birth and thus better suited to doing business in the twenty-first century. Finally, they are under pressure from ambitious firms from developing countries like China, India and Brazil that have honed their business models in resource-constrained environments with large numbers of value-conscious

consumers, making them fundamentally agile and frugal in ways that Western incumbents are not.

Taken together, these trends suggest a bottom-up model of how the systemic global transition to a frugal economy might happen. Given the rise of consumers (especially prosumers who are environmentally active) large incumbents are increasingly motivated to make their business models more frugal. They can no longer rely on their market power to force excess supply on consumers or adhere to wasteful and environmentally damaging practices such as ‘planned obsolescence’ (see [111]).

Given the rise of frugal and agile start-ups and emerging market competitors, large incumbents can also no longer be complacent or inertial. Specifically, given the speed with which small competitors can come on board and the scale with which they can now disrupt business, large incumbents are motivated to move fast to change from wasteful, outdated practices to adopt more contemporary solutions that do better with less (see [23]). Further, in many cases, increasing resource scarcity and corresponding volatility of prices of inputs make it in the strategic interest of large firms (e.g. Unilever) to make sustainability core to their business models. Ultimately, it is the existential threat that global competition poses that drives firms to frugally innovate or die.

While this model is bottom-up and focuses on the role of business, it also recognizes that market processes are often not sufficient on their own for global systemic change to happen. There are bound to be cases of market failure, for instance, when consumers wait for firms to make the first move while firms in turn wait for consumers to change. Such deadlocks require the intervention of a third party, typically the government, as acknowledged in the limitations section below.

(b) Limitations and boundary conditions of the frugal innovation approach

The frugal innovation approach outlined in this paper offers many bottom-up mechanisms for systemic global change. Nevertheless, the approach also suffers some potential limitations as well as boundary conditions beyond which its positive effects hold.

First, economies are complex systems with many different actors influenced by many different forces. This is particularly true of the global economy where structural differences between developed and developing economies combine with trade interlocks within and between regions to create even greater complexity. In such systems, there can be unintended, environmentally damaging consequences of even well-intentioned attempts at change. Attempts to reduce material use in one part of a complex system might only result in increasing material use in another. For example, attempts to reduce driving (and hence the consumption of fuel) could have a rebound effect when consumers use the money that is freed up to take more (flying) vacations or buy more clothes. As a result, emissions might even increase, resulting in ‘backfire’. Druckman *et al.* [56], for instance, estimate that ‘the rebound effect for a combination of three abatement actions by UK households is approximately 34%. They also find that, ‘re-spending on goods and services with a high GHG intensity leads to backfire.’

Second, some technologies and trends that hold out the promise of a frugal economy might not in fact result in the projected environmental and material demand savings. For instance, while additive manufacturing and three-dimensional printing might reduce material demand, they are also (currently) highly energy intensive. Further, while a move to service-based economies might result in less manufacturing-related emissions, it is well known that services also carry embodied emissions. As Xenos [112] puts it: ‘It takes a lot to be a minimalist: social capital, a safety net and access to the internet.’ Finally, while the sharing economy is frugal in making better use of spare assets, its environmental benefits are not entirely clear. As Frenken [113] points out, ‘the jury is out on the environmental benefits of sharing practices that undoubtedly encourage greater efficiency in the use of resources but in doing so lower prices and so encourage rebounds or result in a problem-exchange—sharing clothing but dry cleaning after every use.’

Third, while the frugal innovation approach holds out the promise of a business-led systemic transition to a frugal economy, there are nevertheless many reasons why businesses alone cannot be relied on for such change to happen. Some businesses might have business models that depend on increasing rather than decreasing material demand (e.g. energy hungry manufacturers or oil and natural gas industry firms). Others might have business models that require consumers to buy often and therefore pursue 'planning obsolescence' even when this leads to waste and consumption regret on the part of consumers (see [111]). Indeed, such firms might have motivational reasons to oppose change and lobby to impede and slow it down. Further, even those firms that wish to change, might find it hard to do so for organizational and cultural reasons. Large firms with complex, hierarchical bureaucracies and slow, regulated processes might find systemic change hard to bring off. And even though their inertia might damage their competitiveness, their size and market power might help them to continue to survive and suppress competition from more efficient frugal innovators.

Finally, competitive pressures and market forces alone might not be able to bring about systemic change. In some cases, consumers might be prone to inertia. Even those who increasingly say they care about environmental change might not put their money where their mouths are and back these views up with their consumption behaviour. Indeed, many consumers might wait for firms to make the first move to a more frugal model. Equally, firms might find that it does not pay to change as long as a majority of consumers are conservative and inertial. And so a deadlock might result with both consumers and large firms waiting for the other group to make the first move. Such deadlocks can only be broken by third actors like governments putting into place incentives and punishments that induce either consumers or firms or both to change their behaviour and reduce such cases of structural lock-in (see [114]; see also [47,48] for policy led approaches to material demand reduction).

10. Contributions of the frugal innovation approach to the material demand reduction agenda

The frugal innovation approach makes three potential contributions to the material demand reduction agenda.

First, it takes a systemic view of how the global economy might make the transition to being inclusive yet sustainable. Specifically, it addresses the fundamental dilemma that the world faces of how to meet the needs of 7 billion (growing to 9 billion) humans without bankrupting the planet. For this challenge to be met, the paper argues that it is necessary to look at both supply- and demand-side dynamics. Further, it argues that it is necessary to look at these dynamics in both developed and developing countries. Without such a systemic, global view, attempts to bring about material demand reduction are likely to be piecemeal and prone to failure.

Second, the frugal innovation approach takes a bottom-up view of how key players, particularly large and small firms, can interact with consumers (and vice versa) to bring about a transition to a sustainable economy. Firms are major actors in the global economy: they make a significant contribution to global GDP but also account for a significant proportion of greenhouse gas emissions. Likewise, consumers, through their consumption practices, have an important role to play in material demand reduction. This paper shows how all these players have their own motivations to change (or not) as well as varying levels of power to bring about such change (or resist it). The paper sheds light on the interaction of motives and power of these players through competitive and market processes to bring about change. Such a qualitative and quantitative understanding of bottom-up, organic interactions of real firms and consumers is likely to complement top-down, deductive approaches to the material demand reduction agenda.

Third, the frugal innovation approach has crucial implications for the role of the state versus the market in bringing about material demand reduction. It shows how pressures from consumers for change as well as competition from innovative start-ups hungry for growth can bring about systemic change in an organic way. The state's primary role therefore becomes one of facilitating

this organic approach to systemic change by ensuring a level playing field between large and the small firms, incumbents and new ventures. Further, the state can use its immense power as a bulk buyer of products and services from firms to drive innovation and change. It is only when the market mechanism fails to produce the necessary change (for instance when deadlock occurs between supply and demand) that the state need intervene through regulation and tax-based incentives. The view of the state that the frugal innovation approach propounds is neither antagonistic to business nor *laissez faire*; it is inherently participatory. The state steers the economy rather than doing the rowing.

In conclusion, therefore, this paper argues that for the global economy to grow in a sustainable way, a systemic transformation to a frugal economic and industrial model is needed. This change will require multiple actors to play their role in the process. Large, global corporations will need to change their business models and move to being circular enterprises, using renewable sources of energy and other resources. New ventures will have to expedite this process of change by scaling new frugal solutions, taking on the incumbents where necessary, and working with them to bring about change where this makes sense. Consumers will have to change their patterns of consumption, becoming more responsible in the way they buy and consume products and services in the home and at work. Where the market mechanism on its own cannot bring about such systemic change, governments will need to intervene by using regulation and incentives to foster collaboration and competition as needed. In the developed world, the movement from an old fossil-fuel based, linear economy to a renewables based circular economy can create new sources of sustainable growth in otherwise sclerotic economies. In the developing world, meanwhile, the move to a frugal economy offers the opportunity for countries to leap-frog their developed counterparts and catch up in an environmentally sustainable way. For the globe as a whole, frugal innovation is not only a necessity, it is a positive means of ensuring prosperity and well being for 9 billion people on a fragile and finite planet.

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