Overcoming scarcities through innovation: what do technologists do when faced with constraints?*

Janne M. Korhonen
Aalto University
School of Business
Helsinki, Finland
jmkorhonen@gmail.com

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Abstract

The question that still divides many debates about sustainability is the possibility of technological substitution of scarce natural resources. While there is considerable debate among economists whether technology can mitigate scarcities through development of substitutes, there is little actual research on the mechanisms and limitations of this substitution process. In this study, I seek to build a bridge between scarcity and innovation literatures to study when technologists decide to develop technological substitutes. My starting point is the theory of technology as a recombination of existing mental and physical components. Combining this theory with modern scarcity literature that differentiates between absolute, relative, and quasi-scarcities yields a more nuanced framework for understanding both different types of scarcities, and how technologists decide whether or not to develop or adopt technological substitutes. This improves our understanding of the possibilities — and limitations — of scarcity-induced innovation. I then illustrate the use of this framework with two brief historical case studies about constraint-induced innovation. I conclude that the mainstream economic practice of assuming that substitution will occur automatically, even in cases of absolute scarcity, may hide extremely important phenomena from discussion and debate behind a veil of circular reasoning.

Keywords: Absolute and relative scarcity; Constraints; Porter hypothesis; Innovation; Copper; Jet engines

1 Introduction

An old maxim announces that necessity is the mother of invention. If so, shouldn't humanity rest easy, knowing that technological progress will ultimately overcome whatever environmental and other problems the future may

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bring? Even though debates between proponents of human ingenuity and its skeptics have raged at least since the famous bet between pessimist Paul Ehrlich and optimist Julian Simon (Sabin, 2013), the question itself is surprisingly underresearched. While the Simon/Ehrlich bet was ultimately decided in Simon's favor and many believe the flexibility of market economy can at least in principle mitigate any scarcity, critics have justly pointed out that there are no guarantees human ingenuity and flexible markets will always be able to overcome all obstacles.

Generally, however, the belief in the human ingenuity remains strong. Those who question the possibilities of technological development to mitigate environmental and social ills are often derided as "malthusians" or "luddites," since so far our economy has been fairly resilient despite warnings of imminent scarcities. The "Porter hypothesis" (Porter and van der Linde, 1995) and related research (for an overview, see e.g. Ambec et al., 2011) goes even one step further and argues that scarcities are not just obstacles to be overcome: instead, increasing scarcities such as those put in place by strong (environmental) regulation may even accelerate economic development, as they force companies to develop new technologies. However, quantitative evidence suggests that regulatory scarcities so far have had little effect on the rate of overall innovation (e.g. Newell et al., 1999; Roediger-Schluga, 2004). Nevertheless, even less sanguine observers generally believe that environmental challenges can be mitigated through technological change. Even if scarcities do not accelerate innovation as such, new technologies are believed to eventually replace legacy "dirty" technologies if sufficiently strong inducements, such as regulatory push and pull, exist (e.g. Horbach et al., 2012). This view is implicitly based on dominant neo-classical economic thought, where resource scarcities are eventually solved through substitution triggered by rising resource costs.

Increasingly, critics of mainstream economic thought[1] have expressed alarm that this formulation may not adequately cover the phenomenon of scarcity (Bretschger, 2005; Baumgärtner et al., 2006; Daoud, 2011, 2007; Raiklin and Uyar, 1996; Sahu and Nayak, 1994). These scholars argue that mainstream economics limits itself to the study of phenomenon of "relative" scarcity, which already presupposes that "scarce" goods can be substituted for other goods or that more of the scarce good can be produced by reallocating resources differently (Baumgärtner et al., 2006). However, while innovation response to scarcities has been studied extensively at a macro level (see e.g. Bretschger, 2005), our understanding of what drives technological substitution decisions made by those who actually decide to develop new technologies — the "technologists" — could still be improved (Bretschger, 2005). The open question motivating this study is the decision-making logic of the technologists: when and why do they choose to develop technological substitutes, and when do they adopt other courses of action?

The task of developing empirically grounded insights into the microlevel dynamics of induced innovation largely falls to the lap of innovation studies. Accordingly, an emergent "ingenuity" research stream within innovation and management studies has studied the concept of constraints and scarcities and their impacts for innovation (for overviews, see Lampel et al., 2014; Gibbert

[1] I use the term "economic thought" to separate research on economics from economics-influenced discussions in e.g. policy sphere, or what Kwak (2017) calls "economism".

et al., 2014; Gibbert and Välikangas, 2004). This research has found, for example, that financial constraints may in some cases result to better performance from groups engaged in innovative work (e.g. Scopelliti et al., 2014; Hoegl et al., 2008; Keupp and Gassmann, 2013; Weiss et al., 2014; Katila and Shane, 2005), or that some scarcities have been solved through innovative solutions (Korhonen and Välikangas, 2014; Gibbert and Scranton, 2009; Gibbert et al., 2007). Other works note that "bottom of the pyramid" approaches to lean product development can produce superior products (e Cunha et al., 2014). Nevertheless, there is a gap between these positive micro-level studies and generally negative high-level econometric findings (Newell et al., 1999; Roediger-Schluga, 2004). Some scholars caution against drawing too firm conclusions from the research, as the overall outcomes of scarcities and constraints do not seem to accelerate technological change (Roediger-Schluga, 2004) or may only result to somewhat quicker adoption of technologies that would probably have been adopted anyway Korhonen and Välikangas (2014); Yarime (2007). If the latter case holds true more generally, the prospects of overcoming environmental and other scarcities through technology-enabled substitution become significantly bleaker.

This paper seeks to answer the call put forward by Bretschger (2005) and build links between the scarcity and innovation literature through (mostly) theoretical but empirically informed discussion of the prospects of technology in overcoming scarcities. This study also expands upon prior case studies of scarcity-induced innovation or technological substitution (e.g. Hoogma, 2000; Gibbert and Scranton, 2009; Roediger-Schluga, 2004; Korhonen and Välikangas, 2014) and helps explain why some technologies may be easier to substitute than others.

My focus is on the fundamental choices made by those who develop technologies, rather than on the organizations where the technologies are developed. While the latter are undoubtedly of great importance for understanding how scarcities can induce innovation, the behavior of organizations facing scarcities has been studied in numerous fine studies already (e.g. Weiss et al., 2014; Hoegl et al., 2008; Katila and Shane, 2005; Galunic and Eisenhardt, 2001; Noci and Verganti, 1999). However, these studies are usually limited to financial constraints (i.e. the standard economic scarcity) and do not generally consider whether the technology used might have some influence in the outcome. Furthermore, prior studies have not explicitly addressed the decision-making by technologists (as individuals or as a group), even though it is individual people who actually make the decisions whether or not to attempt to develop substitutes. While the motivations behind important technological decisions are undoubtedly complex, I will attempt to outline some possibly rational reasons why technologists sometimes choose to develop substitutes, and sometimes resort to other means to secure access to required resources or simply cope with the scarcity. Even though this question could be sidestepped in a standard neoclassical analysis by arguing that technologists develop new technologies when the costs of inaction exceed the costs of action, I believe that a more detailed unpacking of the substitution decision would be valuable for advancing our thinking about resource scarcities and technological substitution.

Unfortunately, this focus on technological decisions will require me to abstract out the indubitably important role markets play in scarcity responses: for the purposes of this paper, the resource allocation role of markets is assumed to happen through cost/benefit calculations comparing various technological options. That said, I believe that the analysis can be readily extended to cover the role of markets, should a need arise.

The discussion here is necessarily interdisciplinary, requiring insights from several different research streams. From economics, I build upon recent thinking about the nature of scarcities, and particularly on Daoud's (2007; 2011) concept of "quasi-scarcities" as an additional type of scarcity besides absolute and relative scarcities (cf. e.g. Baumgärtner et al., 2006). From innovation studies, I draw upon increasingly influential theory of technologies as recombinations of existing mental and physical components (e.g. Savino et al., 2015; Fleming, 2001; Arthur, 2007, 2009). This "recombinatory innovation" theory provides a simple yet detailed enough view into inner workings of technological systems and how they can change as a response to scarcities. A particularly valuable lesson learned from recombinatory innovation theory is that the technologies are not alike. The interdependence of technology's components, for instance, can influence the difficulty of altering existing technological systems. As such, it should help us to understand better how, and when, scarcities can help promote innovation that effectively substitutes the scarce resource — and when we should be suspicious of techno-optimist claims.

The paper is structured as follows: first, a brief review of the concept of scarcity in economics, including Daoud's (2007; 2011) concept of quasi-scarcities; second, an introduction into recombinatory theory of innovation, followed by the main theoretical contribution — a model of recombinatory, scarcity-induced innovation. Next, this model is applied to two brief historical case studies to illustrate the mechanism in action. Finally, a discussion and conclusions are provided.

2 Scarcity economics: perhaps everything isn't relative?

A widely accepted definition of modern economics maintains that economics "studies human behavior as a relationship between ends and scarce means which have alternative uses" (Robbins, 1932, p. 15). As Baumgärtner et al. (2006) note, from this it is often concluded that economics is essentially about optimization under constraints, which are merely expressions of scarcities. However, Baumgärtner et al. (2006) and many others (for a review, see Daoud, 2011) have noted that modern, neoclassical economics defines scarcity only in a relative way. In this formulation, in order to obtain more of the scarce good A, one must give up something else, B. However, it is implicitly assumed that more of A will always be available, if only sufficient value of B is exchanged. In many cases, this is a reasonable simplification: as long as elementary resources are fairly abundant, giving up one consumption bundle ("A") allows the production of another bundle ("B"). Furthermore, people are often willing to accept such substitutions. Thus, goods are thought to be substitutable either on the production side or the preference side (Baumgärtner et al., 2006).

The extent to which this is the case in reality is, however, open to discussion. Many scholars argue that in practice, some resources may not be substitutable (e.g. Baumgärtner et al., 2006; Daoud, 2011, 2007; Tchipev, 2006; Raiklin and Uyar, 1996). Common examples include living species, which cannot be replaced if extinct; another example might be bread in a besieged, starving city

(Baumgärtner et al., 2006). Although the distinction between essential and non-essential or "elementary" and "imaginary" needs may be fuzzy (Lähde, 2013), it seems obvious that at least in some extreme cases, some resources do not have viable substitutes. For example, humans need a certain amount of energy (food) to survive: for individual, arguably nothing can substitute for food if starvation is imminent.[2] In such settings, scarcity may occur due to human needs or wants exceeding the available resources. However, the problem can be examined even deeper. In a commendable effort in sorting out various types ofscarcities, Daoud (2011; 2007) synthetized the ideas of famous economists Amartya Sen and Carl Menger into a model of (quasi)scarcities and (quasi)abundances. For the purposes of this study, Daoud's important contribution is the (re)introduction of the concept of quasi-scarcity into scarcity discussion.

By quasi-scarcity, Daoud means a situation where goods are generally abundant, but (quasi-)scarcity still arises in respect of given individuals because of invalid or absent entitlement to said goods (Daoud, 2007). In Daoud's formulation, scarcity arises from a generative mechanism composed of needs R, entitlement E, and goods A. In cases where $R < A$, as is the case with world hunger and food supply (Daoud, 2007), a mediating mechanism E, access, is required for scarcity to occur.

As the purpose of this paper is to chart the decision-making process of individual technologists, the distinction between relative, absolute, and quasi-scarcities is important. While "outbreaks" of absolute scarcities may occur at a system level, technologists generally operate on a lower level. At the firm or industry level, where most of the relevant technological change occurs, sudden onset of absolute scarcity is rare.

More common are quasi-scarcities, where — in principle — a good may be available, but access to the good is restricted. Examples abound in pollution control, where the "good" is the free use of natural "sinks," such as the atmosphere, for the purposes of waste disposal. In most countries, increasingly strict environmental legislation controls how much of this "good" individual firms may use. However, firms may attempt to influence their entitlement and lobby for less regulation. Examples of such efforts to alter firm entitlement are easy to find. For just three examples, one may look at the ignomious fate of the 1990s California Zero Emission Vehicle mandate (Kemp, 2005; Hoogma, 2000), the history of volatile organic compound (VOC) regulation in Austria (Roediger-Schluga, 2004), or the recent diesel car emission scandal, where several governments responded to news of automakers cheating in emission tests by proposing looser emission limits!

Why do technologists choose to lobby instead of developing new, profitable innovations? The short answer is because technologies are not developed from nowhere. No matter how attractive a solution would be, a technologist cannot even conceptualize a technological solution to a problem unless she has the mental building blocks required for the concept, and the concept cannot be

[2]Note though that an individual may choose to starve, for example to save resources for his/her children - or just to make a political point. Arguably, the benefit the individual receives from this decision is therefore a substitute for food. Similarly morbid arguments might be put forward to argue that oxygen in air or any other seemingly non-substitutable resource may also be "substituted." It is therefore a matter of definition and level of analysis whether substitution should be considered possible. For the purposes of this paper, I assume that some resources may be so difficult or ethically problematic to substitute as to be practically non-substitutable.

realized until physical building blocks exist as well. If we want to understand better when we can rely on technology to deliver solutions to scarcities, we first need a working theory for how technologies are replaced with new ones. It is for this reason why we shall now introduce the recombinatory theory of innovation.

3 Recombinatory model of scarcity-induced technological response

Recent years have seen a resurgence of an idea dating back to Schumpeter and beyond (Schumpeter, 1934; Ogburn, 1922): that technologies can be fruitfully understood as systems composed of recombinations of existing "components"(Fleming and Sorenson, 2001; Arthur, 2007, 2009; Frenken, 2006; Fleming, 2001; Murmann and Frenken, 2006; Savino et al., 2015). These components include not just physical artifacts, but also practices and knowledge required to construct a particular technology (Arthur, 2009). Furthermore, technologies and technological systems themselves can become components for further technologies.[3] The recombination is usually performed in organizations such as firms, but it is ultimately the individuals — technologists — that make decisions whether to pursue some avenue of research or to recombine components in a specific manner. While the details of this recombination process are interesting and important (for a review, see Savino et al., 2015), for the purposes of this paper, the details are ignored and the catch-all term "technologist" is used to keep discussion manageable while referring to any decision-making body with power to make important decisions regarding the development of technological substitutes to scarcity.

By thinking about technological systems as combinations and decomposing technologies into their components (and, if necessary, further into sub- or even sub-sub-components) we can consider the interdependencies between the components (Fleming and Sorenson, 2001; Arthur, 2007, 2009; Frenken, 2006). Such interdependencies may in fact be important reasons why some scarcities may have significant impacts on technological systems, while others do not. As such, this theory answers the call put forward by Bretschger (2005, p. 161) for a "better understanding of the mechanisms driving [scarcity-induced] innovation". Finally, it should be noted that in this paper, the terms "technology" and "technological systems" are used rather loosely, following Arthur's (2009) definition of technology as some means for fulfilling a human purpose, whether that purpose is explicit or hazy.

Let us therefore consider an exemplary technological system T (Fig. 1). Let us assume that it consists of only two components X, and Y. These components are connected to each other to form the technological system T, i.e. $T = f(X, Y)$, for the purposes of producing a good A of some value, i.e. $A = f(T)$. The production of A requires two resources, I and O, from outside world. These may be understood as inputs or waste sinks, and may become scarce. Let us

[3]Note that technological systems can be decomposed to different combinations of components depending on the level and purpose of analysis. For example, cars could be considered to be composed of only four main components (engine, drive train, steering and chassis) at one level of analysis (see Frenken, 2006), while at another level of analysis, cars are composed of thousands or hundreds of thousands of components. Similarly, the decomposition would change if we were to consider e.g. "mobility system" as a whole.

further assume that at least one of these resources is required to produce A.

For both of the resources, I or O, there may exist substitute resources $I_{1,\ldots n}, O_{1,\ldots n}$. However, using them may require changes in the technology T (to $T_{1,\ldots n}$). This change is effected by changing the technology's components X, Y to $X_{1,\ldots n}, Y_{1,\ldots n}$. It is worth noting that the components are often composed of sub-components X', Y' of their own, and thus substitution may in fact change a sub-component (or sub-sub-component X'', etc...) of a component rather than the entire component; however, what exactly we consider a component and a sub-component depends on how we wish to divide a technology for analysis, and the division of technology into two components provides enough detail for the theoretical analysis now at hand.

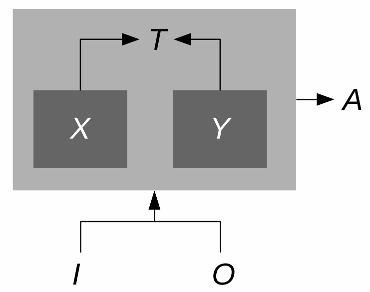

Figure 1: Exemplary technological system.

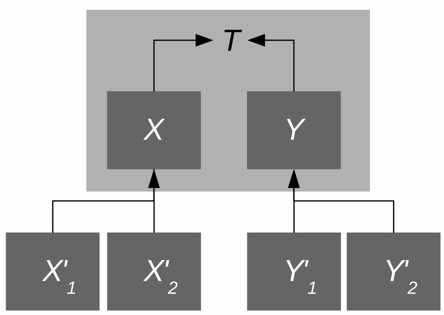

Figure 2: Technology and its sub-components.

Armed with this model of technological systems and Daoud's (2007) notion of relative, absolute and quasi-scarcities, we are now ready to examine how technologies might change as a response to scarcities, and consider the possibilities for substitution.

3.1 Availability of alternative technological components

In order to substitute component X with alternative component X_n, the subcomponents X' required for X_n need to be available in the first place. (An important research finding is that particularly in breakthrough innovations, the needed components may come from an entirely unrelated field; see Schoenmakers and Duysters 2010 or for case studies, Korhonen and Välikangas 2014; Särkikoski 1999). Likewise, if the entire technological system T needs to be substituted with T_n, an alternative capable of producing the good A at some acceptable level needs to be available.

There are good reasons to believe that at least in the short term, scarcities (particularly quasi-scarcities and absolute scarcities) generally promote adoption of already existing, more resource efficient (and, therefore, often more complex) technological alternatives instead of research and development of completely novel solutions (for empirical evidence, see Mickwitz et al., 2008; Kemp and Pontoglio, 2011). Research and development tends to be slow and risky, whereas responses to scarcities are generally demanded relatively quickly. This view is supported by empirical research that suggests the most common response to tightening environmental regulation and other quasi-scarcities is the adoption of existing but more efficient technology (Christiansen, 2001; Mickwitz et al., 2008; Yarime, 2007; Kerr and Newell, 2003). In some cases, these technologies are already in use; in others, they are ready to be taken to use (Korhonen and Välikangas, 2014).

It may be theorized that in the short term, substituting technology T for alternative T_n requires that components X_n and Y_n required for T_n are perceived to be available without much development effort. In case of scarcity, the cost of scarcity needs to exceed the perceived cost of adopting T_n, including possible development costs. In the longer term, it is possible that the scarcity spurs development of the required components X_n and Y_n. However, from this it does not necessarily follow that such components will be found.

3.2 Simple case: no interdependencies between components

In the simplest case, the components X and Y are independent of each other and from each others' inputs and outputs ($X \perp Y$, $I \perp O$). In other words, changing the component X to alternative component X_n in order to utilize a substitute resource(s) I_n, O_n does not require changes in Y. In respect of good A produced at a "normal" equilibrium level A_{eq}, we can then detail the four possible outcomes of generalized scarcity impacting either I or O. For brevity, I shall focus on component X and resource I. Note also that throughout the following discussion, for the sake of the argument I shall assume that the demand for A is fixed. As plentiful literature on scarcity and voluntary simplicity stresses, scarcities can also be abolished if the need for a particular good can be reduced.

1. No alternative component X_n nor substitute resource I_n can be found that can be substituted for X or I so that Acan be produced above minimum viable threshold level $A_0 (A_0 \geq 0)$. This case might be considered as an example of absolute scarcity.

2. Either X_n and/or I_n can be found that allows production above A_0, but below "normal" level A_{eq}.

3. Either X_n and/or I_n can be found that allows production at A_{eq} (or close enough so it doesn't matter). In this case, substitution can be considered perfect.

4. Either X_n or I_n can be found that allows production at *above* A_{eq}. This case would correspond to scarcity-induced productivity improvement as theorized by e.g. Porter and van der Linde (1995).

The *type of scarcity* has bearing on the possible response — or, more accurately, the type of possible response defines the type of scarcity. If we define absolute scarcities as those scarcities where substitution is impossible (outcome 1), we naturally assume that there is no response whatsoever that would correct the deficiency and allow business as usual to continue. At firm or even at industry level, such scarcities are most likely rare, but possible. Individual firms may become bankrupt because of environmental legislation, and some goods (for example, dodo fillets) are simply impossible to produce, even though they were possible to produce at some point in human history.

Similarly, outcome 4 is possible but unlikely in practice. While information asymmetries and organizational inertia may theoretically lead to situations where external pressure (scarcities, in this case) can force the companies to try harder and uncover productivity-enhancing improvements, these situations are likely to be rare (for one formulation of necessary conditions, see Ambec and Barla 2002; for a more thorough review, Roediger-Schluga 2004). Prevalence of such outcomes would beg the question, *why such improvements were not adopted earlier?*

Likewise, outcome 3 is unlikely. Strictly speaking, such an outcome would require that there are no costs associated with substitution. Another possibility could be that while substitution incurs some costs, it also produces some benefits, and the net effect is close enough to zero so as not to matter.

By far the most common case would seem to result to outcome 2 — a loss of production of A. Whereas in outcomes 3 and 4 the technologists would not have much of an incentive to try and improve the supply of the scarce resource and would be, by definition, incapable of doing so in outcome 1, such an incentive is clear in outcome 2. Furthermore, many if not most scarcities relevant to environmental economics today are not due to absolute lack of a resource, but result from regulatory constraints placed on the utilization of a resource. In Daoud's (2007) terms, these scarcities should be properly understood as quasi-scarcities: what the technologists lack is *entitlement* to a specific resource.[4] From this it follows that one expected response from technologists to threatening resource scarcities would be action to improve access to a resource.

Possible actions include, but are not limited to, obtaining more of the resource or increasing the entitlement via market or non-market means. An example of the latter is lobbying in the political sphere. Individual firms and industries can wield substantial political power, generally in proportion to their importance to national or regional economy. "Compliance costs" to regulatory

[4] In Daoud's formulation, "regular" scarcity due to opportunity costs would tend to amount to "relative" scarcity.

constraints are a hotly debated issue whenever new constraints are proposed, and firms often expect politicians to provide generous support if costs are anything but modest (Roediger-Schluga, 2004). Particularly if such support is not forthcoming, firms are known to spend considerable effort in lobbying against legislation, and can manage to add and exploit loopholes to the extent that regulation becomes ineffective (Kemp, 2005).

It would therefore follow that technologists confronting scarcities have essentially three choices: Suffer the impacts of scarcity, substitute i.e. make improvements in their technology in order to cope with scarcity, or improve their entitlement to scarce resources through political action. It might be conjectured that the choice depends on the perceived pay-off, and is influenced by the perception of how difficult or expensive the substitution would be. This brings us to the more complex question: Why some technologies are inherently more difficult to substitute than others?

3.3 Substitution and the interdependency between components or resources

No discussion about the possibilities of technological substitution is complete without a reference to whale oil being substituted by kerosene as lamp fuel, and I do not intend to make an exception. Although the story is not quite as convincing example of technological substitution as it is sometimes claimed to be (see Kovarik, 1998), it serves to illustrate why some substitutions will be inherently easier than others. A major reason why alternatives to whale oil were rapidly adopted was because the fuel was not *interdependent* with oil lamp technology at the time. Users did not have to buy new lamps: they only had to purchase different fuel. In contrast, the replacement of gas lighting by electricity required not only new lamps, but an entirely new delivery infrastructure as well.

The theory of technology as recombinations of components presented earlier helps us to make sense of the importance of interdependencies. Typically, components comprising a technological system are to some extent interdependent from each other. Thus, an alteration of one component or its replacement necessitates alterations in other components. The more alterations are required, the more difficult replacing a particular component will be. Furthermore, required resources may also be interdependent with other components, or required resources may themselves be complementary to each other. In the model technological system described above (Fig. 1), if the good A can be produced with either resource I or O, the inputs are independent ($I \perp O$); if the production (above threshold A_0) requires both, then the resources are interdependent, or complementary. Interdependency of resources increases the difficulty of substitution in the same way as the interdependence of other components of the system.

These interdependencies can be formalized and modeled in various ways. One popular formulation that has been repeatedly used in studying dynamics of innovation and new product development (Frenken, 2006; Silverberg and Verspagen, 2005; Almirall and Casadesus-Masanell, 2010) is the so-called *NK*-based simulation model of complex systems(Kauffman, 1993). Without going deeper into details of this model (the reader is directed to Frenken 2006, for excellent discussion of the model and its application to innovation research, or to Savino et al. 2015 for empirical evidence concerning search and recombination processes), it can be used to conceptualize the design of technological artifacts as a search problem over "design landscapes" (Kauffman et al., 2000; Katila and Ahuja, 2002; Frenken, 2006; Maggitti et al., 2013; Savino et al., 2015). The topology of these landscapes depends on the interlinkedness of technology's components, with one dimension representing "fitness" — in technology studies, usually interpreted as efficiency or quality (Frenken, 2006). As interdependencies increase, the number of trade-offs required also increases: improving one part of the system degrades the performance of another part. Topologically speaking, the number of "local optima" of high fitness regions increases from one optimum (achievable if there are no interdependencies, as then every component can be independently optimized) to many. This is an intuitively appealing formalization of the typical design problem faced by technologists: everything has a trade-off, and the more complex the product, the more complex the trade-offs. Even more importantly, the model shows that moving from one local optimum to another requires alterations in several of the technology's components at the same time.

Therefore, the search for alternative solutions becomes more and more difficult as the degree of interdependency grows. Systems whose components are independent of each other can be relatively easy to adapt to scarcity of some particular component or input: The search for new solutions can be confined to searching alternatives for that particular component or input. But if interdependencies are present, several components or even the entire system may need to be revamped at once. Aside from vastly increasing the theoretical difficulty of the search problem (see Simon, 1969), in the practical realm this may very well mean a requirement to build or to prototype and test a replacement for the entire system instead of its component only. Obviously, this may be an expensive proposition.

3.4 Complexity growth as a scarcity response: is efficient = good?

In this light, technological systems with fewer interdependencies could be considered more resilient and likely to adapt to scarcities through technological substitution. Unfortunately, evidence in form of simulation studies (Altenberg 1997; Kauffman 1993; note that *NK* models are generally not amenable to analytical solutions and require simulation studies), empirical investigations (e.g. Fleming and Sorenson, 2001) and plentiful anecdotes strongly suggests that such "functionally independent" systems[5] would generally be less efficient in their primary purpose than moderately interdependent systems. (Heavily interdependent systems, on the other hand, suffer from "complexity catastrophe" and would be difficult to design in the first place; see Frenken 2006 or Simon 1969 for thorough discussion.) In real-life terms, a system whose components were functionally independent would suffer from significant design penalties: for example, if the skin and chassis subsystems of a car were to be functionally independent, the chassis as a whole would be significantly heavier, as the skin could not be counted to double as a load-bearing component. Thus, in reality, moderately interdependent systems are far more common than systems whose

[5]Strictly speaking, no actual "system" can consist of totally independent components. The term "functionally independent" is therefore used.

components are functionally independent. This is a powerful theoretical explanation for the generally accepted wisdom: efficiency and resiliency are usually mutually exclusive goals.

Ironically, the very pursuit for increased "efficiency" that is often touted as the key technological response to environmental problems, e.g. for climate mitigation, may well make the system as a whole less able to cope with other scarcities. What's more, the drive for improved efficiency usually results to what Arthur (2009, p. 134) calls "structural deepening," where the deficiencies of originally simple technologies are amended by adding more and more complex components. This in turn provides many more opportunities for webs of interdependency to build up and clog the system as a whole. As an example, the early (and by current standards extremely inefficient) jet turbine prototype of 1936 had one moving part and at most some hundreds of parts in total: current jet engines have more than 20 000 parts. Efficiency improvements, a typical scarcity response, usually involve structural deepening and an increase in complexity. This may have repercussions later, if increased complexity makes total system change more difficult.

3.5 The types of scarcity and technological substitution

Assuming a profit-maximizing firm using technological system T (Fig. 1) and a scarcity of resource I, the following lists the five different types of scarcities and technological response, i.e. potential outcomes depending on whether demand for good A is elastic or inelastic. In the former case, there are effectively ample substitutes for A, whereas in the latter case, the scarcity of A itself may be a serious problem.

I. I scarce in the sense of it having an opportunity cost; demand for A elastic: *Relative scarcity.* Standard economic optimization problem. The possibility for substituting technology T or component X by technology T_n or component X_n in order to utilize more abundant resource I_n depends on the availability and cost of T_n or X_n and/or availability and cost of I_n. The substitution cost depends also on the degree of interdependency between technological components: high degree of interdependency suggests (but does not necessitate) that technological substitution is less likely. Can induce development of T_n or X_n over longer term, but is unlikely to significantly accelerate the pace of technological change.

II. I scarce because of insufficient entitlement; demand for A elastic: *Quasi-scarcity of I, relative scarcity of A.* If technological solution is perceived to be within reach, tends to result to technological response depending on cost and availability of T_n, X_n and I_n, as in case 1. However, insufficient entitlement can also be amended through political action, or through a combination of technological substitution (to reduce the impact of scarcity) and political action. Can also induce development, and if alternative T_n exists and will involve only modest loss from A_{eq}, is likely to accelerate adoption of T_n.

III. I scarce because of insufficient entitlement; demand for A inelastic: *Quasi-scarcity of I and of A.* Most likely response is political: inelasticity of demand for A gives the technologist considerable political clout. However, if alternative T_n exists or is perceived to be close to practical feasibility, it is very likely to be adopted as one part of the solution, even if it involves significant loss of value from A_{eq}.

IV. I absolutely scarce; no quick technological or political fixes perceived; demand for A elastic: *Absolute scarcity for I*, *relative scarcity for A*. Leads necessarily to reduced production from A_{eq}. Tends to spur research and development for alternatives and is likely to promote adoption of alternative T_n if such technologies exist, despite potential loss from A_{eq}.

V. I absolutely scarce; no quick technological or political fixes perceived; demand for A inelastic: *Absolute scarcity of I and A*. If I used to be abundant, this situation is likely to lead to problems in broader techno-social system, unless research or political action produces alternatives relatively quickly.

In other words, the existence of absolute scarcity depends on the perceived possibility for substitution. We can talk meaningfully about absolute scarcities only if there are no substitutes for either the scarce resource *or* for the good produced from the resource. Since this is not a common occurrence, it follows that cases of absolute scarcity are rare, and lack of availability of cases to study may alone explain why research so far has largely ignored the possibility of absolute scarcities. (Note that cases where I is scarce but technological or political solutions are readily available are not discussed above; it is assumed that in such a case the substitution decision will be simple.)

It is important to note that since research and development decisions involve essentially predictions about the future, the decisions tend to be based on *perceptions* of what is feasible and what is not. Technologists are unlikely to be able to assess the costs and risks of a development effort reliably enough for truly calculated choices about which course of action to pursue. For this reason, mental models, perceptions and social constructions of the technologists (see Kaplan and Tripsas, 2008) are likely to be of considerable importance for any attempts to assess the likely response to scarcities.

In the following section, I use the model above to illustrate two previously published cases of scarcity-induced innovation.

Scarcity of I

Absolute	IV. Absolute scarcity for *I*, relative scarcity for *A*. Decrease in production of *A*. May promote R&D.	V. Absolute scarcity for *I* and *A*. Can cause societal problems if situation persists.
Entitlement (quasi-scarcity)	II.Quasi-scarcity for *I*, relative scarcity for *A*. Likely responses technological and/or political.	III. Quasi-scarcity for *I* and *A*. Likely response political, unless alternative technology ready.
Opportunity cost (relative)	I. Standard economic optimization problem: production of *A* depends on costs of *I* and demand for *A*.	
	Elastic	*Inelastic*

Demand for A

Figure 3: Responses as a function of scarcity type and elasticity of demand.

4 Example cases: scarcity in jet engine development and copper manufacturing

Technological response to resource scarcities has been studied in two relatively recent case studies, one focusing on the development of jet engines in Second World War Germany (Gibbert et al., 2007; Schubert, 2004; Gibbert and Scranton, 2009) and the other on the development of radically novel "flash smelting" technology in copper smelting as a response to post-Second World War energy scarcity (Korhonen and Välikangas, 2014; Habashi, 1993; Särkikoski, 1999; Habashi, 1998). Drawing on historical approach, these studies illustrate how a perceived scarcity caused technologists to develop novel innovations in response, effectively substituting technology for scarce resources. Both cases have been hailed as exemplaries of potential benefits of scarcity for innovation (Gibbert et al., 2007; Schubert, 2004; Gibbert and Scranton, 2009; Korhonen and Välikangas, 2014; Habashi, 1993; Särkikoski, 1999; Habashi, 1998), and as such, they serve as good examples to demonstrate the framework outlined above. The history serves to tell three stories: two of success, and one of failure, demonstrating how radical changes that cause a cascade of changes throughout the technological system can be too much of an obstacle, as noted in the Section 3.3.

4.1 The substitution of nickel in early German jet engines

The efficiency of a jet engine is heavily dependent on the maximum temperature the engine parts can withstand. The higher the operating temperature, the more efficient the engine can be. In particular, early jet engines were limited by the temperature their turbine parts tolerated. In a jet engine, turbine at the rear end of the engine is powered by hot, expanding gases from the combustion chamber, and convert some of the energy in gas to rotary motion. This motion drives the compressor at the engine's front, pushing more air into combustion chamber between the compressor and the turbine and thus enabling the engine to operate (Fig. 3).

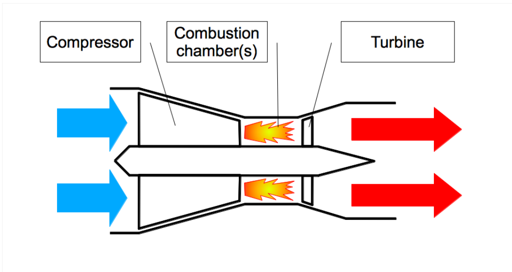

Figure 4: A schematic of a jet engine.

A major problem for turbine design is that turbine blades in particular have to withstand very high temperatures while being stressed by turbine spinning extremely rapidly. Materials suitable for practical jet engines only appeared in the 1930s, in form of nickel-based "superalloys" (Sims, 1984). However, at the time nickel was a scarce strategic resource, essential for a variety of military

Figure 5: Original and modern air-cooled turbine blade cross sections. The original German hollow blade design (left) was made from thin sheet metal; modern turbine air cooling (right) uses very different turbine blades with cast and machined cooling channels.

equipment from tough armor plate to armor-piercing projectiles and machine tools required for manufacturing armaments. In particular, nickel posed a problem for Germany: most of the world's nickel supply was in the hands of the Allies (Perkins, 1992).

4.1.1 The "success: hollow turbine blades

According to some researchers, the nickel scarcity faced by German jet engine designers spurred them to come up with a novel, radical innovation: a turbine whose blades were cooled by air via a system of internal air ducts (Gibbert et al., 2007; Schubert, 2004; Gibbert and Scranton, 2009). Hence, the nickel shortage is argued to have resulted to a remarkable innovation that managed to substitute for scarce nickel.

However, another interpretation of the same set of facts is that the perceived availability of a technological solution may have *exacerbated* the scarcity. The air-cooling concept adopted by the Germans, called the "hollow blade" (that is, a hollow turbine blade made from thin sheet metal) to distinguish it from modern "cooling channel" concept (Gunston, 2006; Kay, 2002, see Fig. 4) had its roots in the pre-war designs for piston engine superchargers (Lorenzen, 1930; Reinburg, 1930; Smith and Pearson, 1950). Turbochargers contain a small turbine, powered by hot engine exhaust, that turns a compressor that forces more air into the piston engine. Thus, they are in effect small jet engines with an external combustion chamber. They share many similarities with actual jet engines (which are powered directly by hot gas generated in the internal combustion chamber) and the early jet engine designers almost invariably had experience with or were inspired by existing turbocharger designs. From the 1920s, German turbocharger designers had experimented with hollow blades to design turbochargers that would both require less nickel (which was known to become scarce if a war were to break out), and be easier to manufacture, as stamped and welded sheet metal blades could be much cheaper to make compared to laborious milling of solid blades (Giffard, 2016). Coming from this background, the German jet engine designers continued to develop hollow blade concepts for both of these reasons, with ease of manufacturing actually being the dominating rationale according to immediate post-war interviews (Sproule, 1946).

Some later recollections indicate that the designers did perceive the nickel scarcity as a pressing one (e.g. von Ohain, 2006). However, as shown by the data collated in Norcross et al. (1947), the scarcity was more a question of insufficient entitlement rather than absolute lack of resource: Germany ended the war with more nickel reserves than it had at the beginning. Even the most ambitious jet engine program envisioned by the Germans would have consumed only a

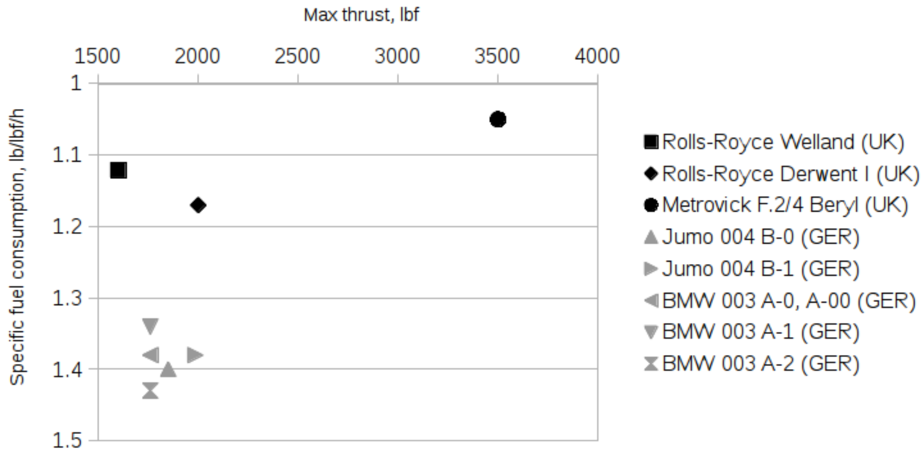

Figure 6: Performance and fuel efficiency of Second World War-era jet engines. Performance (maximum static thrust) increases towards top right. Data from Wilkinson (1946) and Kay (2002).

minuscule portion of the reserve stocks, and would actually have *conserved* nickel resources, even without the hollow blade design: jet engines of greater power could be manufactured with less nickel and other scarce materials than state of the art piston aeroengines (based on figures in Kay, 2002; see also Giffard, 2016). As such, the evidence suggests that the development and promise of hollow blade designs caused the German air ministry to see no reason to increase the nickel allocation to the jet engine program; as a consequence, the designers continued to operate under the perception of nickel scarcity.

While advantageous from the manufacturing point of view, the hollow blade design imposed definitive performance penalties and design complications (Wilkinson, 1946; Kay, 2002, see Fig. 5.). These complications, which included the need to route cooling air inside the engine, illustrate the typical tendency of technological solutions to scarcity to have interdependencies to other components of the system, and how technologies tend to grow more complex in in response to scarcities (see Sections 3.3 and 3.4). These and the performance trade-offs were the key reasons why the British — the other leaders in jet engine development — did not adopt air cooling in their early designs despite testing it (Eyre, 2005; Gunston, 2006). In contrast, the Germans accepted decreased performance, forgoing the slight but very real advantage afforded by more powerful engines in World War II aerial combat. As such, the jet engine case could be seen as an example of Type II scarcity discussed earlier: the demand for good A, in this case performance, was at least somewhat elastic, while the nickel shortage was a quasi-scarcity arising from insufficient entitlement rather than absolute shortage of nickel. Furthermore, as discussed above, the perception of a technological solution being available may have been a factor in preventing the political solution of the scarcity.

In this case, the technologists may not have made a conscious decision to develop a technological substitute for scarce nickel, although the desire to save nickel was clearly a part of the appeal of the hollow blade turbine and contributed to the support the design enjoyed despite protracted development (Kay, 2002). However, by continuing to develop a technology that was likely perceived at least as a partial substitute by their superiors, the *in*decision of German jet engine designers contributed to the perception of scarcity, and to continued lack of entitlement to scarce nickel resources. The demand for performance A was sufficiently elastic to permit some performance penalties, and as a whole, the problem did not become sufficiently acute for a political response (increased entitlement) that is more likely in Type III scarcities, where the demand for A is inelastic.

4.1.2 The failure: ceramic turbine blades

It should also be noted that the nickel scarcity did not cause the German designers to succeed in developing a truly revolutionary design: a ceramic gas turbine. Ceramics, naturally resilient against high temperatures, would in theory have been excellent answers to nickel shortages, as they could have been made from abundant alternative resources. The Germans tried to develop ceramic components such as turbine blades and nozzles for jet engines as well, but they lacked the technological sub-components required to make them work (Kay, 2002). This illustrates nicely the idea put forward in Section 3.1: the required technological components, which may come from an entirely unrelated field, need to be available for scarcity to bring about novel innovations. Even today, practical ceramic jet engines remain in the drawing boards, and it is not clear which technological developments are required to realize them — if that even happens (Gunston, 2006).

While test rigs and some prototype engines were nevertheless built and run with ceramic turbine blades, the use of ceramics necessitated major changes in the overall engine design and eventually rendered the resulting engines impractical from either operational or, more commonly, manufacturing point of view (Kay, 2002). This serves as an example how the inherent interconnections between the components of the technological system may make substitution difficult if not impossible, because changes in one subsystem can cause a cascade of changes throughout the system as a whole.

4.2 Substituting electricity in copper smelting

Another relatively well-documented case where technological development has been claimed to have benefited from scarcity concerns the invention of so-called "flash smelting" technology for copper smelting. When developed in the late 1940s, this technology made possible to eliminate or at least greatly reduce the need for extraneous fuels in smelting copper ore to raw copper, and potentially halved the cost of smelting (Korhonen and Välikangas, 2014; Habashi, 1993; Särkikoski, 1999; Habashi, 1998). As its effluent gases were also easier to clean compared to many previous furnace types, it is no wonder that flash smelters accounted at one point for nearly 70 percent of world's primary copper production (Korhonen and Välikangas, 2014; Särkikoski, 1999).

The roots of this remarkable energy-efficient innovation are often traced to the post-war energy crisis that faced Outokumpu Ltd., a small state-owned copper manufacturer in Finland. As a result of defeat in the Second World War, Finland lost a significant chunk of its electric generation capacity. Just prior to the war, Outokumpu had invested heavily in a large electric smelter, and now had to quickly develop an alternative. The situation was critical: Outokumpu's copper products featured prominently in the war reparations deliveries the victorious Soviet Union demanded from Finland, and a failure to comply might have even been used as a pretext for military occupation (Kuisma, 1985; Rautkallio, 2014). The invention of the flash furnace was later seen as almost an miraculous solution to this pressing problem.

However, while the electricity shortage was the proximate cause for Outokumpu to begin work on flash furnace, the furnace type itself was a result of decades of well-published experiments and practice, and was simultaneously and independently taken into use in Canada (see again Section 3.1). In fact, the alternative design was technologically superior (Korhonen and Välikangas, 2014). Furthermore, Korhonen and Välikangas (2014) argue that Outokumpu had other options at its disposal, and that its politically well-connected managing director Eero Mäkinen could very well have pressured the government, which in any case owned the firm, to divert more electricity or coal (an alternative fuel) to its use. Both resources were scarce, but arguably not absolutely so. Using data on Finnish energy usage and archival records attesting of Outokumpu's importance to the Finnish goverment, Korhonen and Välikangas demonstrate that either of these options could have been feasible when the decision to develop the flash furnace was taken in late 1944, and that they might have been even more prudent choices than embarking on a quest for untested technology. However, the confidence Outokumpu's engineers had on the flash smelting furnace meant that the company's chief decision-maker Mäkinen did not perceive a real need for alternatives, and hence had no pressure to lobby the government for these resources for Outokumpu's use — in stark contrast to the lobbying the same managing director embarked upon when certain other resources, arguably much less critical for Outokumpu, were scarce (Korhonen and Välikangas, 2014).

The pressure from war reparations deliveries suggests that this case could serve as an example of Type III scarcity response: the resource I, energy, was available but not allocated in sufficient quantities, while the demand for A, copper products, was more or less inelastic. While the most likely response might have been political (that is, Outokumpu's managing director lobbying for higher entitlement), the perception that an alternative technology was readily available, combined with the managing director Mäkinen's demonstrated patriotism (Särkikoski, 1999), caused Outokumpu to refrain from squeezing more resources from the hard-pressed government. In this case, the decision-making culminated in a single person: Mäkinen. He had been directing the company since 1918, and was a forceful personality (Särkikoski, 1999; Korhonen and Välikangas, 2014) who by 1944 ran the notionally state-owned company pretty much as his own fiefdom. Research has shown that he perceived flash smelting to be a feasible if not 100 percent certain solution to Outokumpu's problems (Särkikoski, 1999; Korhonen and Välikangas, 2014), and directed the company's engineers accordingly.

The simultaneous "discovery" (more properly, development) of flash smelting in Canada and the long "pre-history" of the innovation (documented by Korhonen and Välikangas, 2014) show that Mäkinen's perception was based on evidence, and that the development of flash smelting was not just a serendipitous discovery. The time was ripe for flash smelting, and the electricity scarcity just provided the impetus for *Outokumpu* to be among the first companies to actually build furnaces implementing the technology. An additional insight worth noting is that several components required (understanding of fluid bed reactions and oxygen generators) came from fields totally unrelated to copper metallurgy, just as discussed in Section 3.1, and that the flash furnace was very much more complicated than the earlier coal-fired and electric furnaces it eventually replaced, demonstrating the structural deepening of a technological system when its efficiency is increased (Section 3.4).

5 Conclusions and discussion

In this paper, I've attempted to shed some light into a question of great practical and theoretical importance: why and when do technologists choose to develop technological substitutes for scarce resources, and when do they act to increase their resource entitlements? The answer that emerges is complex, as is to be expected from such a broad question. There are different types of scarcities, and depending on the maturity of relevant technologies, the possibilities for technological substitution may differ. Building on previous work on the nature of scarcities (Bretschger, 2005; Baumgärtner et al., 2006; Daoud, 2011, 2007; Raiklin and Uyar, 1996; Roediger-Schluga, 2004), one key contribution of this study is to underscore that while the type of scarcity matters, it is actually the perceived possibilities for *mitigating* scarcity that determine how the scarcity is perceived. If the scarce resource can be substituted easily, is it meaningful to speak of scarcities? The answer to this question seems to depend largely on the timescale and scope of the case in question. For individual firms for example, it may not matter if a technological substitute exists, if they lack rights or know-how to use it. On the other hand, such cases may not even register as scarcities on economy-wide level — although Roediger-Schluga (2004) and others warn that industries have political power and are often willing to use it to increase their entitlement to scarce resources, even to the detriment of the society as a whole.

In turn, the ease of which a technological substitute may be found may depend heavily on the particular technology in question. Technologies are not alike, and recent research (Arthur, 2007, 2009; Frenken, 2006) has given us many tools for peeking into their interior, what was once called the "black box." By considering technologies as recombinations of existing components with some interdependencies among each other, and considering the impact of a scarcity as a situation requiring change in one or more components, we can better understand why some scarcities seem to be amenable to technological substitution, while others stubbornly resist the best efforts of Earth's scientists and engineers.

Consider, for example, the "scarcity" of low-carbon energy that is currently imperiling our efforts at preventing dangerous climate change: the reality is that "dirty" energy derived from fossil fuels has become highly interdependent component in the world's economic system. As a result, attempts to replace fossil fuels with cleaner energy are threatened not only by technical difficulties, but by the political power resulting from the numerous interdependencies and the technical and economic difficulty of substitution: it is often easier, cheaper and more reliable to lobby for keeping the entitlement of fossil fuels (or pollution permits) than to completely overhaul the energy system. In contrast, the phaseout of ozone-destroying CFC gases was relatively simple problem, as almost "drop-in" substitutes for most of their important applications were available and phasing out the production of these gases had, at most, a limited impact on the bottom lines of few chemical manufacturers.

Furthermore, given that innovations have to be combinations of available components, it follows that expecting major acceleration of technological change as a result of scarcity is probably going to end in disappointment. If the necessary components are not available, to what extent a scarcity can spur their development? In cases where the necessary components are identified and the innovation is only waiting for further refinements in these components, this is probably possible, although far from certain. The flash smelting case referenced to in this paper provides a good example: According to Korhonen and Välikangas (2014), the technology was "in the air" at the time, generally anticipated by experts and waiting for some firm to adopt it and work out the remaining kinks. But many innovations result from unexpected and unanticipated bricolage of previously unconnected components. If such components are available, scarcity may provide the final impetus required. If they are not, directing research and development efforts to precisely the right components (or sub-components) is going to be difficult, as exhibited by the German failure to develop a viable ceramic turbine. As another example, cheap, large-scale battery storage of electricity has been a goal that has eluded inventors since Edison, even though economic and social benefits would be immense. Maybe technological change marches to a beat of its own, influenced by but not really controlled even by the best efforts of technologists, policy makers and regulators?

Finally, the theory and cases discussed in this paper suggest that while the ability to distinguish between "relative" and "absolute" scarcities may be of utmost importance and the current mainstream economic thought may be lacking in this regard, the cases of technological substitution that have been studied so far seem to be mostly concerned with either relative or quasi-scarcities and insufficient entitlement. The theory presented here provides one explanation why: technological substitution of absolute scarcities may simply not produce cases worth studying, because technologists have little interest in attempting what they expect to be impossible.

These biases may present a dangerous logical trap. As noted above, we generally define the type of scarcity by the ease with which we can mitigate its impacts: those scarcities that are easy to circumvent become, in retrospect, known as relative scarcities, while scarcity of something we can't substitute will be understood as absolute scarcity. However, since almost by definition there are few examples where absolute scarcities have been mitigated through substitution, the studies of substitution are mostly concerned with relative (or quasi-) scarcities. This in itself is not a problem: the problem lies in the way mainstream economic thought tends to assume *based on these studies* that every scarcity will be, in principle, substitutable. In one sense, this is true: every scarcity mainstream economics has so far studied has been solved through substitution of some sort. But what of those cases that leave no story of substitution behind? Is research on economics and technological change really representative in this regard, or dangerously biased? On the other hand, one could probably argue that "absolute" scarcities as such do not exist: even a person dying of hunger may very well choose to die so that someone else has more to eat. Presumably, the dying person will gain some mental reward for such an action that suffices to substitute for dying of hunger. It seems that advancing our understanding of what scarcities actually are and how we should think about them would present a fruitful arena for further empirical and theoretical study.

In conclusion, despite the potential importance of the questions of scarcity and their mitigation through technological substitution, research to the subject is still only beginning. This paper has promoted the use of more nuanced concepts of scarcities and technologies in order to advance the discussion, and found that by some reason or other, much of the existing research may not provide much basis for discussing the potential impacts of absolute scarcities. It remains an open question whether the concept of absolute scarcity has much actual meaning in this sense.

Research-wise, this study should provide some grounds for further studies in the area of technological substitution and technological change as a response to changing resource endowments. If possible, research should try to find examples of absolute scarcities being overcome by technological change or other means. Studies in this topic would help greatly in avoiding the bias described above. Another promising research direction might be the study of the mechanisms of how resource *abundance* (or quasi-abundance) might influence technological change. Finally, since this paper seeks to provide an overview of technological responses to various types of scarcities, focusing in more detail on technological responses to relative-, quasi-, and absolute scarcities might be a fruitful direction for future research. One possibly important link between scarcity and innovation literatures might be forged by examining what organization theory, for example institution theory, might have to say about how quasi-scarcities are formed and perpetuated.[6]

Policy-wise, I hope this study helps to demonstrate that the assumption of technology marching over scarcities through simple mechanisms of supply and demand should at last be laid to the grave where it belongs. The main policy implication of this paper is simple: politics matters a great deal, but while politically enacted quasi-scarcities can sometimes steer innovation to a desired direction, policy-makers should not rely on that happening. Technologists and technological developments can often influence the policy, and if advances to some direction are perceived as impossible, then no amount of political prodding is likely to produce meaningful results, while attempts to do the impossible are all too likely to squander political capital and opportunities. On the other hand, these perceptions can be misleading: whether to trust technologists or not remains a matter of fine judgment. In any case, this study should serve as another justification (if any more are needed) for the importance of broad-spectrum long-term, patiently funded research and development that (sometimes accidentally) produces technologies and components needed for technological substitution. Because components for a breakthrough may come from a surprising source, short-term, narrowly focused research efforts are unlikely promote the development of breakthrough innovations.

Policy-makers should also remember that efficiency and resiliency can be mutually exclusive goals. Striving for maximum efficiency in resource use can result to a system that is, as a whole, less resilient against unexpected chal-

[6]I thank the anonymous reviewers for pointing out these possibilities.

lenges. Structural deepening and increasing complexity of more efficient systems therefore present a challenge to politicians and other decision-makers: Is resource efficiency always a good thing? Answering this question in more detail is another promising and valuable avenue for future research.

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