Challenges in Sustainability

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Cover image
A guy in rural Kenya transporting charcoal to the market to sell.
Photographer: Ann Åkerman

About *Challenges in Sustainability*

Focus & Scope

Challenges in Sustainability (CiS) is an international, open access, academic, interdisciplinary journal dedicated to the publication of high-quality research articles and review papers on all aspects of global environmental and transformational change toward sustainability. Research articles, reviews, communications or short notes and films are welcomed. Manuscripts must be prepared in English; they will undergo a rigorous peer review process, and they will appear online immediately after final acceptance. We especially encourage submissions from early stage researchers.

Objectives & Aims

The objective of the journal is to be a front-runner for original science that stimulates the development of sustainability solutions in an era of global environmental change. CiS defines its place at the interface between natural, socio-economic, and the humanistic sciences, creating a unique platform to disseminate analyses on challenges related to global environmental change, associated solutions, and trade-offs. The journal helps to further the field of sustainability science by bridging gaps between disciplines, science and societal stakeholders while not neglecting scientific rigor and excellence. The journal promotes science-based insights of societal dynamics, and is open for innovative and critical approaches that stimulate scientific and societal debates.

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- Sustainable energy
- Place-based sustainability studies
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- Impact assessment and integrated modeling
- Carbon accounting and compensation

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Challenges in Sustainability

Research Article

Seeking Consilience for Sustainability Science: Physical Sciences, Life Sciences, and the New Economics

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Abstract: The human system, driven largely by economic decisions, has profoundly affected planetary ecosystems as well as the energy supplies and natural resources essential to economic production. The challenge of sustainability is to understand and manage the complex interactions between human systems and the rest of nature. This conceptual article makes the case that meeting this challenge requires consilience between the natural sciences, social sciences and humanities, which is to say that their basic assumptions must be mutually reinforcing and consistent. This article reviews the extent to which economics is pursuing consilience with the sciences of human behavior, physics and ecology, and the impact full consilience would have on the field. The science of human behavior would force economists to redefine what is desirable, while physics and ecology redefine what is possible. The challenges posed by ecological degradation can be modeled as prisoner's dilemmas, best solved through cooperation, not competition. Fortunately, science reveals that humans may be among the most cooperative of all species. While much of the mainstream economic theory that still dominates academic and the policy discourse continues to ignore important findings from other sciences, several sub-fields of economics have made impressive strides towards consilience in recent decades, and these are likely to change mainstream theory eventually. The question is whether these changes can proceed rapidly enough to solve the most serious problems we currently face.

Keywords: anthropocene; cooperation; human behavior; interdisciplinarity

1. Introduction

Human impacts on the planet are now on the scale of geological forces, to the extent that the current era is increasingly referred to as the anthropocene [1]. These impacts threaten to exceed planetary boundaries, risking catastrophic impacts on humans and the rest of nature [2]. If we hope to meet fundamental

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human needs in the near term without destroying planetary life support functions required by all species, we can no longer separate the study of human systems and natural systems, but must instead adopt a transdisiplinary, holistic approach to science that "seeks to understand the fundamental character of interactions between nature and society. Such an understanding must encompass the interaction of global processes with the ecological and social characteristics of particular places and sectors." ([3] p. 641) Earth Systems Science [4] and Sustainability Science [3] exemplify this approach.

The steady accumulation of human knowledge has made it impossible for any individual to be an expert in all areas of study. Scientific progress therefore has relied on increasing specialization in narrow areas, as exemplified by the study of individual disciplines within the universities. This specialization has resulted in impressive advances, but it has also created barriers between fields of knowledge. These barriers are not only serious obstacles to the advance of sustainability science, but also can lead individual disciplines to build on beliefs or assumptions that contradict those of other disciplines. Even if specialization is necessary, it is essential that facts and theories within a discipline are internally consistent, and the facts, theories and inductions from one discipline do not fundamentally contradict those from another. In particular, "when different disciplines focus on the same object of knowledge, their models must be mutually reinforcing and consistent where they overlap" ([5] p. 4). When there is disagreement, it should be settled with empirical tests, experiments and observations to lend support to one hypothesis over another, and not simply ignored. This is very much the case in the natural sciences. Theories in cell biology do not contradict theories in evolutionary biology, and both are consistent with the theories of chemistry and physics. Even when facts and theories may seem to contradict each other, as in the case of quantum theory and the theory of relativity, physicists pay close attention to the contradictions, and assume that they will eventually discover basic physical laws that resolve them. This type of agreement across fields and disciplines is known as consilience [6]. Sustainability science demands consilience as an explicit objective.

Consilience is far less advanced in the social sciences than the natural sciences [7]. Facts, theories and inductions from one social science not only frequently contradict those from another, but also frequently contradict the natural sciences. The most important example of this in the context of sustainability science may be in the discipline of economics for two main reasons. First, economic activity—defined as the transformation by humans of raw materials and energy into goods and services intended to satisfy human wants and needs—is the central cause of the most serious sustainability challenges that human society currently faces: global climate change, biodiversity loss, land use change, ocean acidification, ozone depletion, waste emissions in excess of the planet's absorption capacity, and excessive dependence on rapidly diminishing stocks of fossil fuels. Second, economics arguably has the most influence of any social science on policy decisions. This article will focus on consilience in mainstream economics, which has the greatest impact on policy decisions, and hence the greatest influence on sustainability.

Consilience is not the occasional incorporation of theories or insights from the natural sciences into the social sciences, but rather the explicit acknowledgement that the social sciences must be consistent with the common understanding of fundamental laws that the natural sciences have built up over decades and centuries. This does not mean however that the social sciences should be explicitly modeled on the natural sciences or should blindly adopt its methods. There are profound differences between the two fields. Theories in the social sciences can affect reality while theories in the natural sciences cannot. For example, if people believe the theory that abruptly ending quantitative easing will cause the stock market to crash, this could lead to a panicked sale of stocks, triggering a crash. Eminent mathematical economist Georgescu-Roegen argued that the mathematical models of neoclassical economics—explicitly drawn from the methods of mechanical physics—are ill-suited for the modeling the qualitative change characteristic of steadily evolving economies [8]. Furthermore, though many physicist believe that if we knew the position and velocity of all particles in the universe it would be possible to retrodict the past and predict the future, and some biologists believe that genes determine behavior, the economy should not be described as a mechanistic system devoid of purpose and will, which leaves no room for policy [9]. The social sciences should be informed and shaped by, but not reduced to, the natural sciences [10].

Consilience is also not a one-way street: economists have long called for the natural sciences to become more consilient with economics, complaining about the arrogance of "some scientists in assuming that they are competent to comment on the economic problems of the environment without knowing any economics" [11]. Numerous economists have (correctly) pointed out that limits-to-growth theorists since the time of Malthus have often failed to account for role of the price mechanism and human ingenuity in alleviating resource constraints (e.g. [12–14]).

Economics—conventionally defined as the allocation of scarce resources among alternative competing ends—is a broad field, characterized by many schools of thought with different degrees of influence, some of which have paid more attention to consilience than others. Ecological and biophysical economics for example explicitly strive for consilience with the natural and social sciences [9, 15–19], but these two fields are rarely considered part of mainstream economics. It is in fact a bit difficult to define mainstream economics precisely. An entry in an on-line encyclopedia of economics states that "we are all neoclassicals now… what is taught to students, what is mainstream economics, is neoclassical economics." [20]. Precisely defining neoclassical economics is also difficult. Some authors identify three core axioms: economic phenomena can only be explained as the result of individual actions; all human behavior is an effort to maximize the satisfaction of individual preferences; and equilibrium between supply and demand is the starting point for analysis [21, 22]. Other central themes found in most undergraduate textbooks include the assumptions that humans are rational, self-interested and insatiable, everything can be measured in monetary terms (monism), and preferences are exogenous; furthermore, Knightian uncertainty (immeasurable risk) is ignored, and the desirability of continuous economic growth is taken for granted (e.g. [17, 23]).

In recent decades, serious theoretical and empirical challenges to the core tenets of neoclassical economics have shaken the field, and many economists argue that mainstream economics is transitioning towards greater consilience with the natural and social sciences. Colander et al. [24] argue that at "the edge" of the mainstream, leading economists are incorporating complexity theory, psychology, ecology and institutions into their theories. These leaders are strongly respected by their more orthodox colleagues, resulting in a continual evolution of the mainstream. However, Colander et al. also acknowledge that the mainstream economics of 15–30 years ago (neoclassical economics) is still taught to undergraduates. Hodgson speculates that institutional and evolutionary economics may become the new mainstream [23].

This article focuses primarily on the state of consilience within mainstream economics, while acknowledging the fuzzy boundaries of the field. At one extreme the article will address the material taught in undergraduate textbooks—hereafter referred to as orthodox economics— which is the only exposure most people receive to economics and arguably the most influential on policy decisions [17]. As Nobel laureate and leading textbook author Paul Samuelson stated "I don't care who writes a nation's laws—or crafts its advanced treaties—if I can write its economics textbooks" [25]. At the other extreme this article will address "the edge" of economics, and the new ideas that may be filtering into the mainstream. From the perspective of sustainability, however, The most important area for consilience is in the advice economists provide to policy makers.

Economics is conventionally defined as the allocation of scarce resources among alternative competing ends. From this definition, it follows that two areas of consilience in economics are particularly important. The first is the science of human behavior (e.g. psychology, neuroscience, evolution, and so on), which is relevant to both the ends that economic activity should pursue and the institutions compatible with human behavior. The second is the natural sciences, particularly physics and ecology, which are most relevant to understanding the means required to achieve those ends. We can only decide how to allocate resources after determining the appropriate ends and human compatibility with different institutional arrangements, and the available means, including their physical characteristics.

The structure of the paper is as follows. The first section following this introduction will focus on consilience with the science of human behavior. Subsections focus on rationality, self-interest and satiability, followed by a discussion of the extent to which consilience has occurred. The second section will focus on the natural sciences, with sub-sections on the laws of physics, and the laws of ecology, followed by a discussion of consilience. The third section will focus on the implications of consilience for the allocation problem, with subsections on the physical characteristics of the scarce resources, the laws of economics, and how we should allocate.

2. Human Behavior, Ends and Institutions

Modern economics arose from utilitarian philosophy, which viewed the maximization of utility—the achievement of the greatest happiness for the greatest number—as a moral imperative for society and the desired end of economic activity [26,27]. Since people experience diminishing marginal utility, classical utilitarian philosophy seemed to call for a more equitable distribution of resources. Many economists argued however that a major challenge to maximizing utility was the difficulty or impossibility of objectively quantifying utility or comparing utility between individuals. On the other hand, if people are rational they will prefer things that generate more utility to those that generate less, and their willingness to pay for different goods and services (including leisure and other non-market activities, the costs of which can be interpreted as the income foregone by not working) will reveal their preferences [28]. There is no need to directly measure utility. This result led mainstream economics to redefine utility and welfare as the satisfaction of individual preferences or tastes as revealed by willingness to pay [26, 29, 30]. Utility for society in the current period is therefore maximized when resources are allocated to those willing to pay the most for them, which also maximizes monetary value for the economy as a whole. In the words of a leading economist "the refusal of modern economists to make "interpersonal comparisons of utility" means in effect that they use wealth rather than happiness as the criterion for an efficient allocation of resources" ([31] p. 88). By "efficient", Posner means Pareto efficient (also known as Pareto optimal) in honor of Vilfredo Pareto, a central figure in the development of neoclassical economics. Pareto efficiency is defined as a situation in which it is impossible to make at least one individual better off without making another worse off. Under certain rigid assumptions, markets can be shown to allocate resources in a Pareto efficient manner. The central desired end of economic activity in mainstream welfare economics is Pareto efficiency, equivalent to the maximization of monetary value or economic surplus at any given point in time, brought about by the satisfaction of individual preferences in a market economy. Market competition however leads firms to sell their products at the lowest possible price to cover their factors of production, eliminating economic profit. The pursuit of profit leads firms to innovate, so that consumers can obtain more and better products at a lower price over time. Since a larger economy creates even more wealth, continuous economic growth is another desired end.

These conclusions emerged from fairly rigid assumptions about human behavior, including rationality, self-interest, and insatiability. They also rely on the assumption that we cannot make interpersonal comparisons of utility. The following three sub-sections will examine the rapidly accumulating evidence that refutes these assumptions, much of which was produced by economists at "the edge". The forth sub-section below assesses the extent to which this evidence has affected mainstream economics.

2.1. Are People Rational?

The behavioral sciences, including behavioral economics and neuroscience, have done the most to challenge the notion that humans are perfectly rational. The polymath Herbert Simon first popularized the ideas of "bounded rationality" and "satisficing", which recognized that humans have limited cognitive capacity and limited information, and under these circumstances must settle for satisfactory rather than optimal decisions [32]. Tversky and Kahneman showed in rigorous experiments that human decision-making exhibits systematic biases. For example, most people are risk averse, and weight losses more heavily than gains of equal value. One can frame a single problem in a way that emphasizes either losses or gains and affect the decision making process [33]. As the title of two popular books emphasize, numerous experiments have shown that people are "Predictably Irrational" [34], and we can therefore use our knowledge of human behavior to "Nudge" [35] people in desired directions. Economist Milton Friedman argued that the test of a good theory is not its realism, but rather its ability to generate good predictions [36]; the assumption of economic rationality fails this test.

Neuroscientists and evolutionists have dug deeper into the origins of such seemingly 'irrational' behavior. The human brain has three quasi-independent subsystems with different functions that evolved at different times. Roughly speaking, the 'reptilian' part of the brain is responsible for many automatic and instinctual behaviors, the limbic system is responsible for emotions and related behaviors, and the more recently evolved neo-cortex is responsible for logic, abstract thought and planning for the future. People use different parts of the brain to make different types of decisions, and it is possible to frame a decision in such a way that it elicits a different response initiated in a different part of the brain [37]. Furthermore, "continuous exposure to fixed cultural norms (e.g., religious doctrines, political ideologies and disciplinary paradigms) literally helps to shape the brain's synaptic circuitry in quasi-fixed patterns that reflect and embed those experiences" which leads people to reject information that does not conform to their pre-existing beliefs [38]. In fact, certainty appears to be more of an emotional state than the result of rational thought [39]. This helps explain surveys that show higher levels of education correlate with greater belief in anthropogenic climate change in all groups in the US except Republicans, where the inverse is true [40]; and that conservative white males, particularly those with high self-reported understanding of global warming, are more likely to deny anthropogenic climate change than other groups [41].

2.2. Are People Purely Self-Interested?

Convincing challenges to the notion of perfect self-interest come from a wide variety of fields, including anthropology, mathematical biology, behavioral economics, neuroscience, epidemiology and evolution. Increasing evidence suggests that symbiotic cooperation has played a critical role in major evolutionary transitions, including the emergence of eukaryotes from cooperating groups of prokaryotes and multi-cellular life from cooperating groups of unicellular organisms [42, 43]. Cooperation and concern for others is ubiquitous in humans and likely the major factor contributing to humanity's success [44–47]. Historically, economists used the theory of natural selection to support their assumption of self-interest, arguing that individuals who sacrificed their own fitness to help others would be out-competed by selfish individuals, thus purging altruism from the gene pool. However, mathematical biology has confirmed at least five different paths through which cooperation can evolve: direct reciprocity, indirect reciprocity, kin-selection, spatial proximity, and group selection. The fact that all five occur in humans makes us 'Super Cooperators' [45]. Anthropologists have empirically tested various theories of cooperation in modern communities, finding significant support for them [48], while evolutionists have tested their theories of cooperation against random samples from the anthropological literature, again finding significant support [49].

Perhaps the most interesting path to cooperation is group selection, or more accurately multi-level selection: groups with more altruistic individuals have greater reproductive success than those with more selfish individuals, even though within a given group, selfish individuals may be more fit [44, 45, 49–51]. This results in a population that can exhibit a wide range of genetic pre-dispositions towards pro-social behavior, ranging from purely selfish to highly altruistic. Many cooperative species ranging from slime molds to guppies and humans are able to detect and punish cheaters and favor cooperators, which further promotes cooperation [49, 52]. The need to identify cheaters and cooperators may in fact have played an important role in the evolution of human intelligence [45, 53].

In humans, the genetic capacity for cooperation has been supplemented by culture in a co-evolutionary process. Behavioral economists have devised a series of games that show that people will sacrifice their own welfare to help others even in anonymous settings, and will also sacrifice their own welfare in order to punish selfish individuals. Such punishment appears to be a social mechanism for promoting cooperation, and is thus known as altruistic punishment [54, 55]. Mathematical models show that altruistic punishment, including the punishment of non-punishers, greatly facilitates the emergence of cooperation and is often built into cultural norms [48, 56]. As a result, different cultures exhibit different degrees of cooperation [45, 57].

Another interesting finding is that cooperative species as varied as the prokaryote *Myxococcus xanthus* [58] and the eukaryote *Dictostelium discoideum* [52] cooperate when resources are scarce, but not when they are relatively abundant. This raises the interesting possibility that our competitive market economy is only viable in the presence of fossil fuels, which unleashed a new era of unprecedented resource abundance.

Confirming the biogenetic component of cooperation, neuroscientists have drawn attention to the neurotransmitter oxytocin and its kin, which are found in all animals from fish to mammals. Oxytocin serves as a hormone that stimulates birth contractions in mothers, and as a neurotransmitter that induces a strong feeling of bonding. When people engage in cooperative activities, their oxytocin levels increase, and administering aerosolized oxytocin increases the likelihood of cooperation in experimental games [59, 60]. Oxytocin is also stimulated by sexual activity, and induces sensations of well-being [61]. Perhaps blood oxytocin levels are a more accurate measure of utility than consumption!

Humans are capable of developing institutions that lead primarily selfish individuals to cooperate, or primarily cooperative individuals to be selfish [22, 62–65]. One particularly disturbing finding is that monetary exchange may actually reduce cooperation by crowding out intrinsic motivations [66, 67], and simply priming people to think about money may make them more self-interested [68].

A final challenge to the assumption of perfect self-interest is the compelling study by epidemiologists Wilkinson and Pickett. Their research found that individuals in unequal societies experience higher levels of social and health problems then individuals in more equal societies, regardless of overall levels of income. In fact, wealthy individuals may be worse off in unequal societies than lower income individuals in more equal societies [69]. Humans appear to have an innate concern for fairness [70].

Integrating these insights into economic analysis has profound impacts. Many of the most serious problems faced by society today, ranging from climate change to developing green technologies, can be modeled as prisoners' dilemmas, which are best solved through cooperation [45, 71]. If people evolved to be highly cooperative, if different economic institutions elicit different degrees of cooperation, and if markets can elicit selfish behavior, then it becomes obvious that we must explore a variety of allocative mechanisms in addition to markets [22, 72], such as strategies based on shared production and common ownership [71, 73–77]. If people are inherently social, then we must question the methodological individualism that underlies most microeconomic analysis. If people care about fairness and equality, then just distribution may be more important than Pareto efficiency.

2.3. Are People Insatiable?

The assumption of insatiability also fails to stand up to the scientific evidence. Perhaps the most obvious evidence comes from anthropology. Humans were nomadic hunter-gatherers for at least 95% of their history. As hunting and gathering activities depleted food supplies, tribes were forced to seek out new food sources, often far away. Those who attempted to accumulate more than they could carry would starve [78], so it is hard to envision an evolutionary advantage to insatiability. Nomadic societies were also highly egalitarian, and frequently punished individuals who took too large a share of available resources [49].

Why then are people in general so willing to consume more? Chilean economist Max-Neef suggests that people might believe (perhaps convinced by advertisers) that consuming a certain product will satisfy their need for freedom, affection, participation, leisure and so on. When consuming the product fails to satisfy, they may mistakenly believe that they simply have not consumed enough, leading to a feeling of insatiability [79]. Another problem arises with positional goods, consumed to confer status. Status is a relative concept, and if everyone's consumption level increases equally, then status is unchanged even as environmental impacts worsen [80]. Furthermore, as the rich increase their consumption of status goods, everyone else will feel worse off, and people may make important sacrifices of their own well-being in other areas in order to maintain their status [81–84]. Humans are other-regarding in envy as well as fairness.

This evidence suggests that beyond a certain point, ever-increasing consumption, especially of positional goods, may provide few benefits for society, while imposing serious costs.

2.4. Is the Science of Human Behavior Affecting Mainstream and Orthodox Economics?

Economists at the edge of the mainstream (including many not cited above) have conducted much of the research on human behavior that challenges rationality, self-interest and satiability, with results frequently published in mainstream journals and taught in graduate programs. By these criteria, consilience is underway.

However, while an increasing number of undergraduate textbooks mention behavioral economics, it has yet to change orthodox economics in any meaningful way. Perhaps the most damning evidence here is the consistently replicated research showing that relative to the general population, people who study economics on average behave less cooperatively [85, 86]; prioritize profit maximization over fairness [87]; are more corrupt [88]; and are more likely to free ride [89]. Some of the differences are based on preselection (i.e. more selfish people are likely to study economics) but some are based on indoctrination [90]; in either case this does not bode well for consilience with the behavioral sciences. On the other hand, Bowles' [91] textbook accepts the science of human behavior and evolution as core principles, and may foreshadow a fundamental change in orthodox economics.

From the perspective of sustainability, consilience matters most when the resulting insights are incorporated into policy recommendations. Gowdy and Erickson (2005) argue that despite the fact that "neoclassical theorists have by and large abandoned economic man …the policy recommendations of economists are still based on these outdated representations of human behavior…(and continue) to offer bad advice in dealing with some of the most pressing environmental and social issues faced in the twenty-first century". Gintis [92] concurs that "environmental policies are generally based on a model of the human actor taken from neoclassical economic theory". Focusing specifically on the problems of positional goods, but equally relevant to other insights from the science of human behavior, Frank [93] asks "why does the economics profession take no account of these concerns when formulating economic policy recommendations?", and asserts that none of the responses provide by his colleagues bear scrutiny.

One reason that many economists fail to accept the insights from behavioral economics is the assertion that choice behavior is equivalent to welfare by definition, in which case it simply does not matter how or why people make particular choices. From this libertarian perspective, if we cannot make objective, interpersonal comparisons of utility, then the only objective goal is free choice (e.g. [29, 30]).

However, when economists argue for the satisfaction of subjective preferences as a central goal of economics, they fail to point out that markets weight preferences by purchasing power. Many of the problems central to sustainability concern the allocation of society's shared inheritance from nature. It is hardly value-neutral or objective to assert that we should allocate based on the principle of one dollar, one vote rather than one person, one vote, particularly if people care about fairness. Markets assign a weight of zero to the preferences of the destitute, and systematically allocate resources towards the wealthy. This is particularly troubling for resources that are essential and non-substitutable. Take food as an example. When the prices of grain more than doubled during the food crisis of 2007 to 2008, rich countries such as the USA saw negligible change in consumption; the price of wheat tripled, yet consumption actually increased [94]. The poorest countries in contrast saw a dramatic surge in hunger and malnutrition [95]. Unquestionably, monetary value is maximized by allocating food to an overfed rich person willing to pay a high price rather than a malnourished and destitute family who can afford to pay almost nothing, but it is difficult to accept that this this is somehow optimal, efficient or utility maximizing. In fact, markets arguably allocate the marginal calorie to those who gained the least additional utility from its consumption [96]. The refusal of orthodox economics to make interpersonal comparisons of utility is so extreme however that mainstream textbooks essentially deny the distinction between wants and needs; to quote a typical textbook, "the law of demand puts the concept of basic human 'needs' to rest, at least as an analytical concept" ([97] p. 259). Denying physiological needs is denying basic science.

If I prefer oranges and you prefer apples, it may be impossible to determine if the utility I receive from oranges exceeds what you receive from apples, and allocation based on willingness to pay seems perfectly reasonable. However, to whom society decides to allocate resources required to satisfy physiological necessities is an ethical issue, not a question of preferences [98, 99]. This is especially true if those resources are a gift from nature.

While science can tell us much about the desirable ends of economic activity, which ends should be prioritized is ultimately an ethical question. Science may however be able to contribute insights into ethical issues. One hypothesis is that ethics is the result of gene-culture evolution designed to promote human cooperation, and hence the survival of the species. Jot down a list of five ethical behaviors and five unethical behaviors. You are likely to find that ethical behaviors put the group ahead of the individual, while unethical behavior puts the individual ahead of the group. Most religions similarly call for putting the group ahead of the individual [50]. Consilience with either the sciences or humanities would force economists to reconsider the goal of maximizing monetary value, particularly for essential resources.

3. What Do the Physical and Life Sciences Tell Us About Scarce Resources?

Consilience with the social sciences and humanities would force mainstream economics to reconsider what is desirable; consilience with the physical and life sciences would force it to reconsider what is possible. Conventional economics emerged at a time when natural resources were vast relative to human demands. The recently unleashed power of fossil fuels provided access to previously unavailable mineral resources and unprecedented quantities of renewable resources. Surplus output allowed society to allocate more resources towards science, and technological advances further enhanced humanity's resource base [100]. Economists came to assume that technology could always find a substitute for any given resource, to the point that they could safely ignore natural resources and focus entirely on capital and labor as the scarce means of production [101]. When economists again began to occasionally incorporate natural resources into their production functions in the 1970s, raw materials, capital and labor were treated as substitutes, as though one could make more bread from the same flour by adding more cooks and ovens [102–105]. Economists largely treated technology as manna from heaven, and virtually ignored the importance of cheap and abundant energy [106]. The power of fossil fuels however has allowed us to deplete natural capital stocks and increase waste emissions to levels that diminish the ecosystem's capacity to reproduce and to sustain critical functions. Economics can no longer ignore the laws of physics and ecology and the natural resource base on which society and the economy depend [9, 18, 107].

3.1. The Laws of Physics

From the laws of physics we know that it is impossible to create something from nothing. All economic products result from the transformation of raw materials provided by nature. Furthermore, it is impossible to create nothing from something. All human made products break down, wear out and eventually fall apart, returning to the environment as waste. The extraction of raw materials from nature and the return of disordered waste are known as throughput. Simply maintaining existing capital stocks in the face of entropy requires continuous flows of throughput [108].

We also know from physics that the transformation of raw material inputs into economic products and waste requires low entropy energy, irreversibly converted through use into high entropy waste. Recycling energy without net energy loss is impossible [18, 109]. Finite stocks of fossil fuels account for nearly 90% of all energy used for economic production. We can use fossil fuels almost as fast as we like, but once used they are gone forever. New technologies have recently helped increase gross oil production, but with increasingly high energy costs per new barrel extracted, hence lower net energy and higher greenhouse gas emissions per barrel [110, 111]. The renewable alternatives to fossil fuel are available in vast quantities, but most are highly diffuse, difficult to capture, transport and store, and flow at a fixed rate over time [107, 112]. Sustainability demands that we deplete fossil fuel stocks no faster than we master the technologies required to bring alternative energy sources on line [108].

Economists must account for at least three distinct categories of factors of production, that are essentially complements, not substitutes, and that have different characteristics: raw materials, capital, and energy. Raw materials—which Aristotle called material cause and Georgescu-Roegen (1971) dubbed stock-flow resources— are physically transformed into economic products at a rate we choose, and use equals depletion. Capital and labor—which Aristotle called efficient cause and Georgescu-Roegen (1971) dubbed fund-service resources—transform raw materials into products that benefit humans at a given rate over time. Fund-services are not used up in the act of production, but rather are worn out and must be maintained. Fund-services require energy, such as fossil fuels, food or sunshine. As an example, a bakery requires flour, cooks, ovens and energy (food for the cooks, electricity for the ovens). Labor and capital, both fund-services, can substitute for each other, but are complements to flour and energy. A more efficient stove uses less energy, which could be construed as substitution at the margin, but once maximum efficiency has been achieved, no additional substitution is possible.

Finally, the most basic laws of physics and mathematics tell us that exponential increases in efficiency or exponential growth of any physical subsystem of a finite system can at best be transient phenomena [113]. One dollar invested in the year 0 at 6% interest would now have the same value as a ball of gold (at $1300 an ounce) filling our solar system to the orbit of Pluto. The economy is a physical system, and cannot grow indefinitely.

3.2. The Laws of Ecology

The laws of ecology are almost certainly more tightly binding on economic activity than the laws of physics, though often far less understood. Many of the raw materials (stock-flow resources) physically transformed into economic products alternatively serve as the structural building blocks of ecosystems (funds that generate a service). Society can largely determine how fast to deplete available raw material stocks, such as trees in a forest. A particular configuration of ecosystem structure creates an ecosystem fund that generates a flux of services over time. The ecosystem fund is not physically transformed into the services it provides (e.g. a forested watershed is not transformed into flood regulation), but humans have little direct control over the rate at which these services are provided (a given hectare of forest can absorb only so much water per day). When ecosystem structure is removed and waste returned, often in novel forms to which ecosystems have not had an opportunity to adapt, ecosystem functions are affected: remove the trees or kill them with acid rain, and rain water rapidly flows over compacted soil into the adjacent river, causing flooding downstream. Many of these services are essential to sustaining life, including the capacity for ecosystems to regenerate [114, 115].

Ecosystems exhibit the non-linearity, positive and negative feedback loops, surprises and emergent behavior characteristic of complex systems [116]. They are also poorly understood, so we rarely know in advance the long (or even short) term impacts of our activities [117, 118]. Many ecosystem services are characterized by critical thresholds, beyond which they will flip into entirely different states, potentially far less amenable to the survival of humans and other species, and this may hold true for the global ecosystem as well. In most cases, we do not know where thresholds lie, nor do we know precisely what will happen if we exceed them [119, 120].

One of the major challenges in economics is to determine how much ecosystem structure should be converted into economic products, and how much left intact to generate ecosystem services. Two basic laws apply. First, humans cannot degrade or deplete any element of ecosystem structure (e.g. fish, forests, or fresh water) faster than it can regenerate without eventually crossing some threshold beyond which that component of the structure is gone, or else the ecosystem itself crosses an irreversible threshold, with often unpredictable but potentially catastrophic results. Enough structure must be left intact to maintain the flux of ecosystem services upon which humans and other species depend. Second, humans cannot emit waste into any finite system at rates greater than it is absorbed, or else waste stocks will accumulate, eventually harming humans and/or the ecosystem in potentially catastrophic ways. Unfortunately, failure to acknowledge the central importance of the life sciences to the field of economics has led us to surpass these limits [121]. It is now essential to reduce resource extraction below regeneration rates and waste emissions below absorption rates until stocks are restored to levels compatible with ecosystem resilience and the continued provision of ecosystem services. The longer we take to accept ecological limits to economic production, the greater the reductions required.

3.3. Are the Sciences of Physics and Ecology Affecting Mainstream and Orthodox Economics?

To achieve consilience with the physical and ecological sciences, economists must place energy, natural resources and waste at the core of their discipline, and distinguish between fund-service (labor, capital, ecosystems) and stock flow (raw materials) resources. Economists must recognize that converting ecosystem structure into economic products and emitting wastes inevitably degrades ecosystem functions and accept the urgent need to limit throughput to levels that do not threaten life support functions of ecosystems. The implications of these changes for sustainability are obvious, but do not stop there. One reason that economists pay little attention to distribution is that their models show that factors of production (including labor) are compensated according to their marginal product, which is considered fair. Including either natural resources or energy in economic production functions reveals that factors of production (e.g. labor and capital) are not awarded according to their marginal product [122–124], which would force economists to pay more attention to distribution. Acknowledging that virtually all economic activity degrades ecosystem services inevitably leaving some individuals worse off would force economists to abandon the criterion of Pareto efficiency.

An increasing number of economists are acknowledging that energy is an essential and non-substitutable factor of production [18, 123, 125–127], but many simultaneously acknowledge that "[v]irtually all of modern economic growth theory assumes that GDP growth per capita is driven by technological progress and capital investment, including knowledge investment" and "does not take into account energy availability or prices" [122]. Similarly, many economists recognize that nature provides essential and non-substitutable benefits to humans while stressing that mainstream economists assume endless substitutability [19, 96, 128–130]. The emerging field of degrowth economics recognizes that the current level of economic activity already overwhelms planetary boundaries and calls for economic contraction in the aggregate to create ecological space for economic growth in the poorest countries. Again however, these economists almost inevitably distinguish themselves from the mainstream, where the goal of endless growth is considered the norm [131–134].

In the second update to Barnett and Morse's [12] Scarcity and Growth, Simpson et al. [106] provide an excellent summary of neoclassical economists' treatment of natural resources, energy and the environment as it has evolved over time. They conclude (though do not necessarily agree) that "majority opinion is that even in relatively short periods—years, even months—substitution possibilities obviate resource scarcity" ([106] p. 6). The justification for this belief is that scarcity leads to a price increase that creates the incentives for substitution, efficiency, or developing new substitutes. Orthodox economists often view technology as manna from heaven, which allows economic growth to continue forever. For example, a classic article by Solow [135] shows technology continuously increasing the efficiency with which we use fossil fuels so that we can continue to produce just as much from ever smaller quantities. Economists at least recognize that many ecosystem goods and services are public goods that generate no price signal—a market failure that must be corrected before substitution is guaranteed. More modern growth models view technology as endogenous and also subject to numerous market failures, but in general still conclude that endless growth is possible as long as suitable policies ensure adequate investments in technology [136].

Of course, few economists are calling for continuous physical growth of the economy, but rather for producing more from less, arguing that "nobody can define a finite absolute minimum material input required to produce a unit of economic welfare" ([137] p. 12). However, just as one dollar grows exponentially in value to equal a ball of gold the size of the solar system, continuous exponential growth in economic welfare, however measured, is likely to be equally impossible, and would eventually lead to a state of relentless bliss.

Economics is a huge field, and undeniably a growing number of economists are integrating ecology and physics into their work, for example in the study of ecosystem services, natural resources and climate change [138–140]. What really matters however is the extent to which this translates into advice for policy makers and education for the next generation of economists. The standard proxy for the size of the economy, GDP, makes no adjustments for the depletion of raw materials or energy, yet most economists and politicians alike call for its continuous growth, in spite of its widely recognized flaws [141, 142]. College textbooks in mainstream economics largely ignore energy, and most focus entirely on labor and capital as factors of production. Some textbooks do mention natural resources, but invariably suggest that capital, labor and technology are substitutes. Even more advanced courses in natural resource and environmental economics generally assume unlimited substitutability between raw materials and capital and focus on continuous economic growth. Most mainstream economists focus on Pareto efficiency, ignoring the fact that the resource extraction, fossil fuel and waste emissions that are the unavoidable consequences of economic activity invariably have negative impacts on others.

4. Implications of Consilience for the Field of Economics

If economics achieved consilience with other sciences, it would be forced to completely rethink the problem of allocation both within and between generations. How we should allocate depends on the desired ends, the physical characteristics and status (e.g. abundance or scarcity) of the available resources, human behavior and existing institutions. Some of these factors are dynamic to at least some extent, and as they change, so too must the institutions and mechanisms required for allocation.

4.1. Physical Characteristics of Available Resources

Before describing how true consilience would affect economics, it is necessary to describe two important characteristics of the available resources. The first is known as excludability in economic jargon. A resource is excludable if it is possible for one person or group to use it while denying access to others. Access to such resources can be rationed, which is necessary for markets to exist. When a resource is non-excludable, anyone who wants can use it, and rationing is impossible. Excludability is a policy variable that can be implemented to different degrees, though some resources, including many ecosystem services, are inherently non-excludable. It would for example be impossible to ration access to a stable climate or the ozone layer's ability to protect us from ultraviolet radiation.

Rivalry is another important characteristic. A resource is rival if use by one person leaves less for others to use. All stock-flow resources are rival. For example, if one person cuts down a tree to build a house, that tree is no longer available for others to use. Some fund-service resources are also rival. For example, the more of the waste absorption capacity for greenhouse gas emissions used by the USA, the less is available for other nations. When global emissions exceed absorption capacity, they accumulate as harmful atmospheric stocks. A resource is non-rival if use by one person does not leave less for others to use. If a forested watershed prevents damaging floods, landslides and erosion, the benefits captured by one person living in the regions affected do not leave less for others to use. Only fund-services can be non-rival.

Non-rival resources are not scarce in an economic sense and there is therefore no need to compete for them. In economic terms, abundant, rival resources are similar to non-rival resources. For example, a towel on a beach or a car on the road leaves less space available for another towel or another car, which is the definition of rivalry. However, when available space on the beach or road is abundant, there is no competition for use, and the resource appears to be non-rival. Road tolls, beach entrance fees or other policies can ensure that spaces remain abundant. This has led many economists to argue that rivalry is a policy variable. In fact, rivalry is a physical characteristic that cannot be affected by policy [9]. No policy can change the fact that burning a barrel of oil leaves less for others, or the fact that additional people adopting a technology for energy efficiency does not reduce its effectiveness for those who adopted it first. Information is more than just non-rival: it actually improves with use [143]. Information is also essential for all economic production and must play an important role in addressing our current ecological crises.

4.2. The 'Laws' of Economics

Modern economics emerged at the end of the 18th century, when natural resources were relatively abundant and per capita consumption of human made goods and services a tiny fraction of what it is today (Delong [144] estimates that real global GDP per capita has increased more than 30 fold since 1800). Increasing the output of human made products was arguably the best way to improve human welfare, and markets an effective way to achieve this goal. Most economists therefore focused on market allocation. The market price mechanism allocates scarce resources towards the products that add the most monetary value then rations those products towards the consumers willing to pay the most for them. The rule for achieving this outcome is to keep producing or consuming until rising marginal costs equal diminishing marginal benefits. The logic is straightforward: when marginal benefits exceed marginal costs then increasing consumption of a single commodity or of economic production as a whole increases total utility. However, if marginal costs exceed marginal benefits, then additional consumption makes us worse off. Diminishing marginal utility, rising marginal costs, and the equimarginal principle of optimization (i.e. halting consumption when MB=MC) are treated as basic laws of mainstream economics.

Mainstream economics generally focuses on diminishing marginal utility for individual commodities: the first 2000 calories you consume per day provide far greater benefits than the next 2000. The same rule applies however for aggregate consumption. In general, people spend their first units of income on basic necessities, such as food, water, shelter and clothing. As we earn more income, we buy increasingly less essential commodities with increasingly smaller contributions to our well-being. This means there are diminishing marginal benefits to increasing consumption, and hence to economic growth. The marginal costs of economic growth however are rising. As individuals in a competitive market, we pay the same nominal price for each additional unit we consume. However, when we work to produce things or earn money, we sacrifice the opportunity to engage in other activities we might enjoy more. As we work longer hours to earn more money, we must sacrifice increasingly desirable alternative activities, so the real cost of consumption rises. At the same time, if we accept the laws of physics and ecology, for any given technology, increasing economic production requires the conversion of larger quantities of raw materials and energy into economic products and waste, sacrificing more ecosystem services. Logically, society will sacrifice the least important ecosystems and services first, and must therefore sacrifice increasingly important services with increasing production. Eventually, the rising ecological costs of economic growth will exceed the diminishing marginal benefits, and growth becomes uneconomic, meaning that it makes us worse off [145]. New technologies may allow us to produce more from less, but there are limits to efficiency improvements, and the inexorable laws of exponential growth will ultimately take over. Furthermore, efficiency improvements often result in greater resource use, not less, and the same is true for economic growth [146].

Eventually, as we convert more ecosystem structure into economic products and return more waste, we run the risk of crossing critical ecological thresholds and imposing unacceptable ecological costs on society. When we cross a threshold, a marginal change in activity leads to a non-marginal change in outcome. If the threshold involved leads to the loss of an entire species or ecosystem, we must compare the marginal benefits from the activity with the total value of the species or ecosystem that is lost into the indefinite future [147]. Given the law of ecology that everything is connected to everything else [148], the total value may be unpredictable in advance, and may not be realized for decades or even centuries [149]. Balancing marginal costs with marginal benefits is no longer appropriate.

The central focus of an economics consilient with laws of ecology and physics should no longer be about maximizing the monetary value of market goods and services. Rather, the first priority should be to ensure that economic activity does not lead us to cross critical ecological thresholds, ranging from nitrogen emissions to biodiversity loss and climate change. With current technologies, this may be very difficult. For example, Rockstrom et al. [2] estimate that nitrogen emissions must be reduced by 70% if we are to avoid such thresholds, while greenhouse gas emissions must be reduced by at least 80% [150]. With current technologies it is not obvious that we can reduce emissions by that much and still feed 7 billion people. Major investments in research and development in agriculture and clean energy will be required. Even when safely distant from critical thresholds, economists should focus on ensuring that the marginal ecological costs of economic activity do not exceed the marginal benefits, even though direct comparison of the costs and benefits may be difficult or impossible.

4.3. Resource Characteristics and Allocation

Markets are unlikely to be a suitable mechanism for achieving these economic goals. In the absence of excludability, anyone who wants can consume a resource whether or not they pay, and hence are unlikely to voluntarily pay in a competitive market or a in a culture that promotes self-interest. Ecosystem structure and mineral resources are typically excludable under existing institutions, and can easily be converted into market commodities. However, the ecosystem services lost from removing structure and emitting waste are frequently non-excludable. Markets do not compensate for their provision or penalize for their loss. The result is over consumption, under-provision and degradation. This dynamic explains anthropogenic climate change, land use conversion, biodiversity loss, and most of the other serious problems currently faced by society.

One solution is to make the resource excludable so that it becomes possible to ration access. It is impossible to make services such as climate regulation, disturbance regulation or protection from UV radiation excludable, but it is generally possible to regulate or make excludable the activities that destroy these services. However, making something excludable requires collective action via social institutions; it is a prerequisite for market allocation, and not the result of markets. If sustainability is a goal, then society must step in to regulate access to ecosystem structure and waste absorption capacity to ensure the adequate provision of ecosystem services. Mainstream economists often argue that simply establishing tradable private property rights will automatically lead to efficient allocation, so who receives those rights is relatively unimportant [151, 152]. However, as we saw above with the case of food, market allocation often forces those with the greatest level of physiological need for a resource to reduce consumption the most. If we limit land use change, biodiversity loss, freshwater and nitrogen to ecologically sustainable levels, food prices will likely skyrocket and the poor will starve, which is not socially sustainable. If humans do indeed care about fairness and the well-being of others, then price-rationing of essential resources—especially those freely provided by nature—is inappropriate. Deliberative democratic processes give equal weight to everyone's preferences, while markets weight preferences by purchasing power. Which of these approaches to use is about the distribution of power. Furthermore, ubiquitous externalities rule out Pareto efficiency as a useful criterion, since virtually all economic activities have negative impacts on others.

But rationing access is not always a solution. Non-rival resources are not depleted through use, and rationing access therefore reduces benefits without affecting costs. Such resources are not scarce in an economic sense, as there is no need to compete for them once they exist—though there is competition for any rival resources that might be required to produce or protect them. Markets are only efficient (i.e. able to balance marginal costs with marginal benefits) for resources that are rival. Paradoxically, the economic surplus (the monetary value of total benefits minus total costs) from non-rival resources is maximized at a price of zero where anyone who wants can consume the resource. This is especially true for clean technologies that replace polluting ones. However, at a price of zero, market supply is also zero. Economic systems must still allocate resources towards the production or protection of non-rival resources. Private property rights to non-rival resources, (e.g. patents) provide market incentives to supply them, but simultaneously reduce the economic surplus they generate. The appropriate allocation mechanism is some form of cooperative (e.g. publicly financed) provision that rewards innovators while making their innovations freely available [71, 153].

Many of society's most important resources, ranging from global climate stability and clean energy technologies (information) to biodiversity and critical ecosystem services, are non-rival and inherently non-scarce, challenging the very definition of economics. Most of these resources are also inherently non-excludable so that rationing access is also impossible. However, global society has been strengthening intellectual property rights for decades, using prices to ration access to many of the technologies required to solve our global problems [154]. For example, if we develop a clean, efficient, decentralized form of solar energy, no matter how much solar energy one country captures, there will be no less for others, and the technology itself is likely to improve through use. Patenting the technology and charging for it will reduce use and hence the potential for reducing climate change [71].

If people were inherently self-interested and competitive, as typically modeled by orthodox economists, then we would be forced to rely on economic institutions that channel that behavior towards the common good, such as markets. Behavioral sciences however show that humans are capable of cooperation, and can build institutions that enhance our innate propensity for pro-social behavior. As discussed above, markets may actually undermine cooperation.

If economists hope to contribute to sustainability science, they must take a scientific approach to economics that builds on insights from the physical, life, and social sciences. Objective physical characteristics of resources, not ideology, determine whether competitive or cooperative allocation is most efficient. Table 1 briefly describes potentially suitable mechanisms for allocating different types of resources. While versions of this table are fairly standard in the economic literature, most economists treat problems resulting from non-excludability and non-rivalry as market failures, externalities that should be internalized through market prices. An economics that was more consilient with advances in other fields would instead recognize that economic activity unavoidably degrades the environment, environmental degradation is one of the greatest threats to human welfare, and most environmental problems take the form of prisoners' dilemmas that can only be solved through cooperation. Economics should therefore strive to develop the cooperative institutions required to solve these problems, and abandon its obsession with private property and markets.

Table 1. Resource Characteristics and their Implications for Allocation.

	Excludable	Non-excludable
Rival and scarce	Potential market goods, e.g food, oil, land, consumer goods, but with inevitable negative externalities, ruling out Pareto efficiency as a decision tool. Rationing is desirable, but price rationing of essential resources is problematic.	Open access regimes e.g. absorption capacity for greenhouse gasses; oceanic fisheries: rationing is desirable, but requires cooperation and collective action.
Rival and abundant (club or toll goods)	Club or Toll goods e.g. beaches, parks: rationing desirable when scarcity is a threat.	Rationing is desirable when scarcity is a threat, but requires cooperation and collective action.
Non-rival	Tragedy of the non-commons e.g. patented green technologies: rationing undesirable. Open access is more efficient, but requires cooperation and collective action.	Public goods/open access resources e.g. climate regulation, flood regulation, open source information: rationing undesirable and impossible. Cooperative provision is essential.

4.4. Conclusions

There is little question that the discipline of economics is in a rapid state of flux. Leading economists at the edge of the mainstream are undoubtedly incorporating ideas from the science of human behavior, physics and ecology, and these are slowly filtering down into the mainstream. Even ideas from decidedly non-mainstream fields such as ecological and biophysical economics are becoming more widely accepted. Consilience is occurring. Unfortunately, there is less evidence that the sciences are having much impact on the economic orthodoxy, which is widely taught to undergraduates, or on the advice given to policy makers. Perhaps this is to be expected however, as academic disciplines tend to evolve slowly.

At the same time however, the economic system is also in an extremely rapid state of flux, and its impacts on global ecosystems are unfolding at an unprecedented pace. Since the 1950s, the human population has more than doubled, the use of petroleum has nearly quadrupled, and economic activity has increased by a factor of fifteen. Ecological impacts have increased at the same pace [1]. Economists can no longer afford to ignore basic principles of ecology and physics. Solving these problems will require new economic institutions based on cooperation, and such institutions must be based on detailed knowledge of human behavior. A few decades ago, stocks were long-term investments held for years. Today, they are held for seconds [155, 156]. Foreign currency transactions used to be strictly regulated. Today, annual transactions are more than twenty times global GDP [157]. In complex systems, such rapid and powerful changes can have profound impacts, such as the financial crisis of 2008, which caught most economists completely unaware. The financial crisis undoubtedly pales in comparison to the more slowly unwinding ecological crises we now face. Economists can no longer afford to ignore the fact that the ecological-economic system is a complex, adaptive system subject to surprise and emergent behavior.

Economic theory must evolve at least as fast as the economic system if it is to help society face 21st century challenges. When unfolding events falsify theories from mainstream and orthodox economics, those theories must be abandoned. We cannot passively await progress at the edge of economics to filter through to practitioners and textbooks over coming decades. Consilience must be aggressively pursued as a core principle of economic theory.

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Research Article

Mobile Open-Source Solar-Powered 3-D Printers for Distributed Manufacturing in Off-Grid Communities

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Abstract: Manufacturing in areas of the developing world that lack electricity severely restricts the technical sophistication of what is produced. More than a billion people with no access to electricity still have access to some imported higher-technologies; however, these often lack customization and often appropriateness for their community. Open source appropriate technology (OSAT) can overcome this challenge, but one of the key impediments to the more rapid development and distribution of OSAT is the lack of means of production beyond a specific technical complexity. This study designs and demonstrates the technical viability of two open-source mobile digital manufacturing facilities powered with solar photovoltaics, and capable of printing customizable OSAT in any community with access to sunlight. The first, designed for community use, such as in schools or makerspaces, is semi-mobile and capable of nearly continuous 3-D printing using RepRap technology, while also powering multiple computers. The second design, which can be completely packed into a standard suitcase, allows for specialist travel from community to community to provide the ability to custom manufacture OSAT as needed, anywhere. These designs not only bring the possibility of complex manufacturing and replacement part fabrication to isolated rural communities lacking access to the electric grid, but they also offer the opportunity to leap-frog the entire conventional manufacturing supply chain, while radically reducing both the cost and the environmental impact of products for developing communities.

Keywords: Appropriate Technology; Distributed Manufacturing; Open Source Hardware; Photovoltaic; Solar Energy; 3D-Printing

1. Introduction

Modern energy access is still far from universal, as 1.4 billion people lack access to electricity [1], which directly contributes to multidimensional poverty throughout these regions [2]. Although two-fifths of South Asia's population, primarily living in rural areas, have no access to the grid, more than three quarters of the population of Sub-Saharan Africa (587 million people) in both rural and urban areas are without electricity [3]. This situation appears to be static as rural electrification is a major challenge [4] and as the International Energy Agency (IEA) estimates that if rural electrification continues at the present rate, electricity access will only keep pace with population growth until 2030 [1]. Although some manufacturing occurs in communities without access to electricity, the technical sophistication of what is produced is limited. People with no access to electricity still have access to some higher-technologies, which are imported and lack all customization and often appropriateness for the community. Considering only energy-related devices, for example, throughout the developing world there are broken windmills and micro-hydropower installations, empty biogas pits, rusting charcoal kilns, and unused solar cookers [5] or tractors and water pumps in poor condition [6]. Often the local failure of such technologies, which are employed in many communities, is the lack of appropriateness for a specific community (e.g. difficulties in access to parts and capacity to perform repairs, evolutionary capacity of the technology, predetermining risk factors) [6–8]. Thus there is a need to ensure appropriate technology (AT) is used, this can be defined as those technologies that are easily and economically put to use from resources readily available to local communities, whose needs they meet [9]. The technologies must also comply with environmental, cultural, economic, and educational resource constraints in the local community [9]. Earlier definitions of AT have recently been extended by Sianipar et al. to include technical, economic, environmental, social, cultural, judicial, and political specifications [8]. To meet these requirements the diffusion of information technologies (e.g. cell phones and the Internet) has enabled a commons-based open design or 'open source' method to accelerate development of AT [10–12]. In parallel to the open source movement in software, open source appropriate technology (OSAT) is gaining momentum as it allows technology users to be developers simultaneously and share the open "source code" of their physical AT designs, and to use this ability as a science and engineering education aid [13–20]. OSAT is AT that is shared digitally and developed using OS principles. Thus, rather than computer programs, the "source code" for AT is material lists, directions, specifications, designs, 3-D CAD, techniques, and scientific theories needed to build, operate, and maintain it. One of the key impediments to the more rapid development of OSAT is the lack of means of production of open source technologies beyond a specific technical complexity.

This barrier is being challenged by the rise of open manufacturing with open-source 3-D printers [21], affordable versions of which are capable of replicating any three dimensional object in a number of polymers and resins [22–25]. The most striking of these 3-D printers is the RepRap, so named because it can fabricate roughly half of its own components and is thus on the path of becoming a self-replicating rapid prototyper [23–24]. Recent work has shown enormous potential for open-source 3-D printers to assist in driving sustainable development via digital fabrication and customization [26]. For example, there is currently a collection of open source designs useful for sustainable development [27] including peristaltic pumps, hemostats, and water wheels on Thingiverse, a repository of digital designs of real physical objects [28–30]. Most importantly RepRaps allow users in any location the ability to custom manufacture products that meet their own needs and desires.

In order for rural communities to have access to the benefits of 3-D printing of OSAT they will need electric power from locally available renewable resources such as solar photovoltaic (PV) technology which converts sunlight directly into electricity. PV has already been shown to be a technically viable, environmentally benign, socially-acceptable and increasingly economical method of providing electricity to both on grid and remote communities all over the world [31–37]. Solar PV-generated electricity is particularly well suited for small scale off-grid applications because of the relatively modest power draws of open-source 3-D printers, and it will be addressed here.

This paper provides a description and analysis of i) mobile community-scale and ii) ultra-portable open-source solar-powered 3-D printers including component summary, testing procedures, and an analysis of energy performance. The devices were tested using three case study prints of varying complexity appropriate for developing community applications, while measuring electricity consumption. Results of this preliminary proof of concept and technical evaluation of the use of solar PV to power mobile RepRaps for distributed customized manufacturing are evaluated and conclusions are drawn.

2. Methods

2.1. RepRap Background

RepRaps can currently print with ABS, polycaprolactone, polyactic acid (PLA), and HDPE among other plastics and generally cost between \$30–50 kg^{-1} [23,25]. PLA, which is used here for tests, fits the definition of AT as it is derived from renewable sources, is recyclable and bio-degradable. In addition, printed PLA with a RepRap has been shown to be as strong as commercial prints [38]. The extruder intakes a filament of the working material, heats it, and extrudes it through a nozzle. The printer uses a three co-ordinate system, where each axis involves a stepper motor that makes the axis move and a limit switch which prevents further movement along the axis. The printing process uses sequential layer deposition, where the extruder nozzle deposits a 2-D layer of the working material, then the Z (vertical) axis lowers, and the extruder deposits another layer on top of the first. In this way it can build three dimensional models from a series of two dimensional layers. It should be noted that other heads are under development that would allow for a greater range of deposition materials [23,25,39–42]. It should be pointed out here that any of the RepRap class of 3-D printers can be deemed appropriate for this application. The FoldaRap was chosen as the final prototype here as it is commercially available. It is a RepRap that folds down, as its name implies, into a small footprint and is thus relatively easy to transport. Today there are many easily transported RepRaps.

2.2. Power Requirements

Here only standard RepRap solid polymer filament extruders are considered. Their power requirements based on a number of options are shown in Table 1.

The total power necessary will also be determined by the processing options as shown in Table 2. Power was measured with a multimeter (± 0.2%).

Table 1. Power requirements of RepRap variants.

RepRap Name	Power printing (W)	Power heating (W) Time (min^{-1})*
LulzBot Mendel	35 W	140 W 1–2 min^{-1}
Prusa Mendel	37 W	130 W 1–2 min^{-1}
FoldaRap	40 W	135 W 1–2 min^{-1}

Note: it should be noted that the tests in this study were performed on a heated bed to represent a worst case scenario. The heated bed can be avoided by printing on blue painters' tape with PLA or with a glue-stick on glass, but such appropriate surfaces have not been found for all plastics.

Table 2. 3-D printer processing power requirements.

Option	Price	Power (W)	Operating System	Notes/References
Raspberry Pi [43]	$35 (+monitor)	3 W (+monitor draw)	Linux	Pros: very inexpensive, large online community support, RepRap software available on Linux Cons: potentially long delivery times
APC 8750 [44]	$49 (+monitor)	13 W (+monitor draw)	Android 2.3	Pros: larger processor than Raspberry Pi, Cons: no available software, would have to write new program, not yet readily available, high power consumption
Efika MX Smartbook [45]	$199	3 W–6 W	Linux	Pros: runs Linux, battery life of up to 7 h so no extra power draw, Wifi & 3G for downloading new designs, lowest cost for highest functionality Cons: higher cost
Control through cell phone via Bluetooth [46]	$29 (with existing cell)	1 mW–5 W	Android	Pros: cell phones widespread, "cool" factor Cons: current software needs improvement, can only print designs already in hand
Use only an SD card slot [47]	$35	0 W	N/A	Pros: ultra low power, very low cost Cons: can only print designs already in hand, no community design
Tablet	$150–500	7.5 W–10 W	Varies	Pros: no extra power draw on system, readily available Cons: higher cost

Option	Price	Power (W)	Operating System	Notes/References
OLPC [48]	$100–200	2 W	Linux	Pros: large user community, already scaled in developing world Cons: expense, difficulty running some software

2.3. Designs

Here two types of designs are considered: i) mobile community-scale and ii) ultra-portable open-source solar-powered 3-D printers.

2.3.1. Community-Scale Mobile 3-D Printing

The community-scaled device is designed to be appropriate for a school or a community center that enables many shared users in a community to utilize the equipment. The first portable solar powered RepRap was a Mendel variant using off-the-shelf components [49] and running RAMPS1.3 with an SD card add-on which allowed it to save power by printing without a computer connection. This system was designed for heavy usage. The 2 x 220 W PV panels, and 4 x 120 Ah batteries give the user 35 hours of printing with a single charge. The system uses an inverter to convert the DC energy from the PV and batteries to a standard AC signal. A standard power bar can be hooked up to the inverter, so it can run/charge multiple laptops or printers at once. The frames of the solar panels are reinforced and hinged together so that the faces of the PV modules fold together to prevent damage during transport. There are adjustable, drop-down legs affixed to the modules, so they can be angled accordingly for maximum sun exposure. The community-scale PV+RepRap system is shown in Figure 1a and the design schematics are shown in Figure 1b. The complete bill of materials and assembly is documented here in [50].

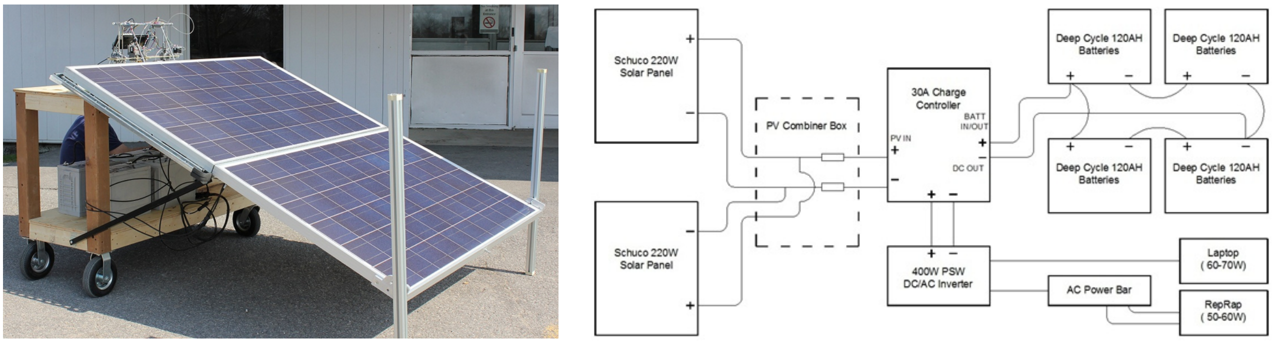

Figure 1. a) Community-scale PV-powered open-source RepRap 3-D printer system for off-grid community use and b) the basic schematic design. The PV are connected in parallel; a combiner box is used to combine and drive the DC supply towards a 30 A charge controller, which maintains the controlled charging and discharging of the batteries. The batteries are connected in two parallel lines with each line containing two unit cells in series. During charging periods four 120 AH batteries are fed DC current while discharging continues to power the RepRap and the laptop through a DC/AC inverter.

2.3.2. Community-Scale Mobile 3-D Printing

An ultra-portable open-source solar-powered 3-D printer has also been designed. This system can be easily transported in a suitcase and is intended to provide complete mobility so as those visiting an isolated community (e.g. doctors) can bring it with them to print necessary products on site in the field. Although not solar powered, a team from MIT has already reported on developing a suitcase 3-D printer [51] and there are other portable 3-D printers currently on the market, including Printrbot Jr (v2), Portabee, Bukito Portable, Taz, Tobeca (which comes in a case) and the Foldarap. Here the ultra-portable system is based around the FoldaRap shown in Figure 2a. It is a RepRap variant, designed by French engineer, Emmanuel Gilloz [52]. The FoldaRap is built on an extruded aluminum base that is designed to fold into a 350 x 210 x 100 mm frame. The ultra-portable solar-powered suitcase 3-D printer is shown packed and deployed in Figures 2b and c, respectively. The design schematics are shown in Figure 2d.

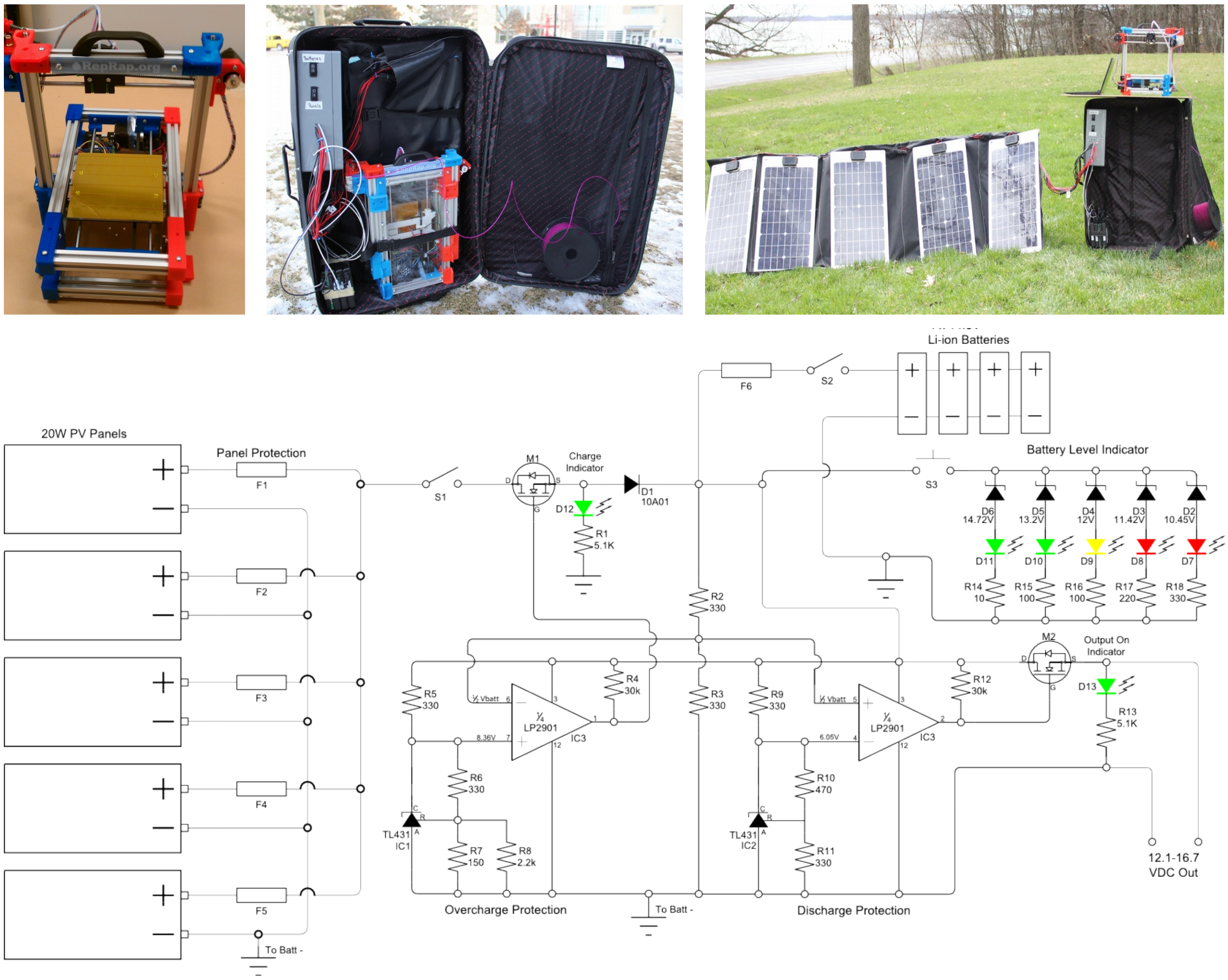

Figure 2. a) Foldarap, b) ultra-portable PV-powered open-source suitcase Foldarap 3-D printer packed, c) deployed for printing, and d) the circuit diagram. An ATmega328 based Arduino Uno microcontroller board is employed to control the charging unit. A current sensor, a temperature sensor and a shunt circuit are provided to keep records and avoid unwanted damage to circuit components. A 16 x 2 LCD display is used to monitor mode of operation. No DC/AC inverter is included; instead a DC/DC charge controller is used. The charge controller follows the voltage divider rule in order to control the supply voltage, and feeds steady current to the Foldarap.

The Efika MX Smartbook, an 'ultra-portable' notebook, was chosen to control the printer. Its power runs at an average of 3 W, compared to the standard 60 W from other commercial notebooks. The Smartbook's battery can easily last 7 hours on a single charge. Running the printer off from an SD card was considered, but in this case only parts that were already stored on the SD card would be printable. To ensure new parts could be designed and printed on site, a computer was necessary. Although the Smartbook was chosen for this project, it is not considered a must-buy component if the builder already has a laptop with sufficient battery life.

To achieve full mobility in this model light-weight, semi-flexible PV modules were used. At 0.95 kg a piece, these modules greatly reduce the size of component that comprises the largest footprint on the community-scale model. The PV modules are comprised of high-efficiency mono-crystalline silicon cells. The bulk and weight are reduced by placing the cells on an aluminum backing, and coating them with a clear gel, replacing the traditional large aluminum frame and glass panel front. This system uses five 20 W modules, to give 100 W at just over 10 lb. The modules are mounted on a durable nylon fabric enclosure to prevent damage during transport.

The other main weight reduction from the community model is in the batteries. Lithium-Ion batteries are used in the portable model for a high storage density in a lightweight package. Although there are denser battery chemistries emerging on the market, Li-ion best fits the goal of a low-cost system. This system uses four 14.8 V 6600 mAh laptop batteries. An inverter was not used in this system, as multi printer/laptop functionality was not required. The circuit is designed to solely run the printer, which requires 12–30 VDC. The complete bill of materials and assembly instructions are available at [53].

2.4. Measurements and Case Study Designs

The rate of battery charging with the PV monitored and correlated with detailed methods that had previously been used to determine solar flux using Open Solar Outdoors Test Field equipment and systems [54] and the state of charge of the battery were measured. Three representative designs were used for testing, as shown in Figures 3a, b and c: 1) avocado pit germination holder [55], 2) cross tweezers [56] battery terminal separator [57]. The latter was used in the construction of the ultra-portable solar-powered suitcase printer from Figure 2. The volumes of plastic used were 8.96 cm^3, 3.47 cm^3, 6.91 cm^3 respectively. All of the prints were downloaded from Thingiverse under CC-BY or public domain licenses, a repository of open source designs that currently with over 455,000 designs and is growing exponentially [58], and were chosen from a selection of designs with the OSAT tag. It should be pointed out here that in general Thingiverse licenses would not offer any application problems in development. The one potential exception is creative commons non-commercial licenses, which could still be printed by community members although they could not be sold. The prints were chosen for varied print difficulty, times and volumes. The cross tweezers being one of the smaller end of expected print times, and the battery holder being a standard print. The cross tweezers require a fine enough resolution to test the accuracy of the printer. The following slicer settings were used for the experiments: 2 perimeters, 4 horizontal shells (2 top, 2 bottom), 35% infill, 1.7 mm PLA, and 200° C for the hotend and 55° C bed temperatures, respectively.

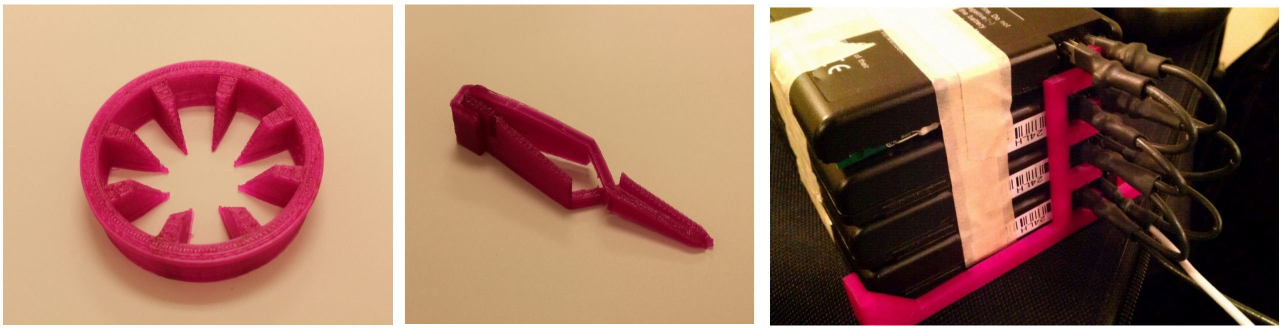

Figure 3. OSAT printed on the ultra-portable PV-powered open-source suitcase Foldarap 3-D printer a) avocado pit germination holder, b) cross tweezers and c) battery terminal separator.

3. Results and Discussion

The three case study prints were successfully printed on both device designs and example prints are shown in in Figure 3. The size of the battery bank in the first design ensured that hours of continuous printing would be available to a community every day there was adequate sunlight. The much smaller battery bank needed for ultra-portability in the second design, however only enables a few prints per day on one charge. The actual parts able to be printed are determined the solar flux availability, the fill density and slicing settings, and the size and geometric complexity (more complex parts take longer and use more energy to print as the head moves without printing). Table 3 summarizes the state of charge of the batteries and print time on the ultra-portable printer from Figure 2. The heated bed and extruder only took an average of 2 minutes to get to target printing temperatures on the suitcase printer. Once printing, an average of 40 W was used, decreasing the expected amount of energy use and increasing the length of time the batteries can last on a single charge. The cross tweezers came out with a slight warp, as one end started lifting from the bed during the print. This might have been prevented by using a 60° C bed temperature rather than the 55° C that was used.

Table 3. Print time and change in charge state of test case study 3-D prints.

Case	Change in State of Charge in Percent	Print Time (min)
1 Avocado Pit Germination Holder	18.1	49
2 Cross-Tweezers	12.9	34
3 Battery Terminal Separator	17.5	50

The results of this study are applicable to any off-grid community in the world with access to sunlight. Both the community-scale and individual suitcase portable PV-powered RepRaps were found to be functional and viable for digitally fabricating custom OSAT on location. The ability to easily fabricate custom and complex parts or products at exceptionally low-cost offers people anywhere in the world the ability to print themselves out of poverty as they can print items to meet their own needs, those of their community, and export items to sell [58]. As the RepRaps are capable of printing both their own components for replacement and are able to upgrade themselves as the global community improves the design, RepRaps have an extended life cycle and are appropriate for most communities.

The related work with RecycleBots, which turn waste plastic into 3-D printing filament, can be viewed as a major enabling technology as it allows local materials to be used in the production of high-value 3-D printer parts, with lower costs and less environmental impact [59–63]. Plastic waste is common in many developing communities [64,65] and informal waste recycling is sometimes conducted as an economic activity [66]. ProtoPrint in India is already using waste pickers to recycle plastic into 3-D filament as part of a social entrepreneurship program. Similar efforts are underway with the Ethical Filament Foundation and Plastic Bank's social filament program. For regions, with no access to waste plastic, further work is needed in biopolymer reactors to produce PLA from agricultural waste. Similarly, access to the electronics in parts of the developing world may be limited. Thus, there is a generalizable risk of repeating the past problems with broken equipment meant for development (e.g. pump parts) by creating a new problem of broken 3-D printers. Future work is needed in developing RepRaps capable of fixing and printing electronics components. It should be pointed out here that this is not a complete solution, but a path towards sustainable development that is still under construction.

The initial costs of the community and suitcase systems as designed here were $2,500 and $1,300 respectively. These costs are still substantial, particularly for the majority of the developing world. These were prototypes and the costs of the systems can be expected to drop considerably for any replication of the systems for two reasons. First the cost of PV has dropped from the $1.59 W^{-1} for which the community panels were purchased and $1.90 W^{-1} for the suitcase panels to under $0.65/W for PV on the international market. Similarly, the cost of the open-source 3-D printers has been reduced from the start of this study at $800 and $600 for the Mendell RepRap and Foldarap to currently about $550 for a Michigan Tech HS Prusa RepRap design [58] and under $500 for a MOST Delta RepRap [67]. Both of these major costs appear to be able to continue to fall. The value of owning or having access to a printer is also increasing exponentially along with the number of open source designs—as producing only 20 common objects with a RepRap in 25 hours of printing at home could save consumers $300–$2000 [58]. It should be pointed out that this study [58] is for wealthy developed countries. Most of the products printed are not available in areas of the developing world and of questionable utility for sustainable development. For developing communities, printed items that bring high value would need to be identified and designed. In addition to the high economic return from deploying PV+RepRap systems for distributed manufacturing, there are also substantial reductions in the environmental impact of manufacturing using this process rather than standard manufacturing [60–62].

Both RepRaps and Recyclebots are open-source technologies where hundreds of people throughout the world are collaborating to rapidly improve the technology and provide an incredibly fast growing selection of products to print with them. This provides the potential of a major paradigm shift in how industry works, which encourages local and even home-made manufacturing of a rapidly increasing selection of highly sophisticated and valuable products. These technologies and the open source paradigm hold the promise of creating enormous wealth for those in developed and developing communities. Perhaps the most immediate change for the developing world will be access to high-quality customized scientific equipment at unprecedented low costs (e.g. reduction by a factor of 100 in the costs of lab supplies and instrumentation) [15,16]. As this becomes commonplace there will be an accelerating positive feedback loop—the more scientists participate the faster technical problems will be solved and the more value will be created for everyone.

4. Future Work

There are several areas of future work that need to be addressed. First, continual reductions in the energy consumption of RepRaps will reduce the size and cost of the PV and battery storage systems for both designs. There has been preliminary work into printing with either a variable area heated bed or printing without a heated bed; the heated bed is the system's major energy draw and needs to be considered in more detail. In addition, a reduction in energy use is possible through the removal of all AC-DC conversions by avoiding standard computer power supplies. The design methodology used here was not formalized and thus the overall design can be improved in the future by following focused design methodologies such as Ecodesign [68,69] or Design for Sustainability [70] and, rather than using the PV-powered RepRap as only a means to manufacture AT, begin to specifically design it as AT itself [71].

This study should also be repeated with recycled waste plastic as several commercial RecycleBots are maturing and the concept of ethical filament is expanding worldwide. The RecycleBot and accompanying shredder/grinders will also need to be adapted for off-grid use with PV power. There is a large collection of designs and the beginnings of open-source digital OSAT designs, but far more work is needed to have printable designs to meet all of the needs of the world's people. Future field work could interview people living in a wide range of developing communities to find out what the most valuable and relevant OSAT prints are in different geographic regions. Considerable work is needed here, but it is also possible for relatively modest contributions of CAD for OSAT to have a major impact on communities all over the world. This work is now being completed largely by volunteers and hobbyists within the 'maker' movement. However, there is also a business opportunity for companies to profit from an open-source hardware paradigm paralleling the open source software movement that has led, for example, to RedHat, which is a $1 billion software company that distributes free software. In particular, companies that sell consumables or 3-D printer components, such as hot ends, should consider open-sourcing the designs for the products that drive the demand in the consumables and move them into new markets. Finally, in order to minimize costs while ensuring optimized designs, all of the components of the system need to be completely open source, including the possibility for printable PV [72] and a fully open source laptop.

5. Conclusions

This study designed and demonstrated the technical viability of two open-source mobile solar photovoltaic digital manufacturing facilities. The first, designed for community use such as in schools, is semi-mobile and capable of nearly continuous 3-D printing using RepRap technology while also powering multiple computers. The second design, which can be completely packed in a standard suitcase, is intended for specialist travel from community to community in the developing world to provide the ability to custom manufacture open source appropriate technology as needed, anywhere. These designs not only bring the ability to complete complex manufacturing and replacement part fabrication, to isolated rural communities lacking access to the electric grid, but they also offer the opportunity to leap frog the entire conventional manufacturing supply chain while radically reducing the environmental impact of production.

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Editorial

Challenges in Sustainability: Another Brick in the Wall

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Dear reader,

We are proud of Challenges in Sustainability's (CiS) fruitful start. A variety of quality research articles, editorials and notes have been published on a range of themes and topics, including sustainability governance [1], improved cookstoves [2,3], the potentials of 3-D printing in the global South [4], and the need for consiliences between the natural and social sciences and the humanities [5], to name just a few. Furthermore, despite the journal's short history, we are pleased with its high visibility, where numerous articles have been viewed or downloaded over 1200 times since publication. The high exposure rate and the quality of publications affirm our aspirations for stable growth and development in the future.

Much of CiS's early success can be acredited to the competent and devoted administrative, managerial and editorial staff. We must first begin by thanking former Editor-in-Chief, Jürgen Kropp, for his work in establishing and placing the journal on a solid footing for the future. Much of the success can also be attributed to the diverse, but impressive, editorial group with competencies in a multitude of sustainability-relevant areas, nor must we forget the devoted managerial and administrative staff at the journal. Thank you all!

Pathway Forward

Notwithstanding our progress, we will continue to work diligently to place CiS at the forefront of sustainability knowledge dissemination, not as a highbrow and inaccessible outlet for academic research and discourses on sustainability; our intentions, rather, are to promote the journal as an innovative forum for cutting-edge research, opinions and notes on sustainability (science).

The first step in this process is an updated *focus and scope* [6] which, we feel, better encapsulates the changing nature and the *state of the art* of today's sustainability research and the myriad debates and discourses that surround it. In addition to the journal's timely review process for knowledge prompt dissemination to wider audiences, we will also work actively to promote special issues on specialized cutting-edge themes in the field. Discussions are already underway on topic areas. Furthermore, we will work to promote CiS as a novel instrument for the promotion of alternative forms of knowledge dissemination, e.g., short films [3], forms that are likely to catch the attention of the new generation of savvy multimedia consumers and decision-makers, both in- and outside of academia.

Finally, we will strive to be an innovative forum to link knowledge on sustainability to action. Because CiS is open access, it has the potential to reach broader audiences. Librello, our publisher, leads the change in academic publishing where large scientific journals and publishing houses historically played an important role in science by creating a network for the circulation of information. However, in the digital era, the traditional network can actually work against the exchange of information by means of high subscription rates and pay-per-view barriers. As one reaction, a boycott against Elsevier was started in 2012; it now counts roughly 15000 scholars [7].

Open access publishers have increased in number rapidly, contributing to the free-availability of knowledge. Nevertheless, the open access system has an intrinsic problem: the revenue of a company is proportional to the number of its publications. Several publishers of dubious reputation have been surfing on this wave and taking advantage of an academic market, which pressures the scholar toward productivity indices based on the number of his/her publications [8,9].

Librello is an environment sponsored and supported by scholars and their institutions. Our membership program allows us to keep the decision of publication from any economic pressure, and we rely on our editorial team of experts to take decisions impartially. Our system also benefits the authors, since the annual membership fee covers multiple submissions. We aim at working closely together with scientists and experts outside academia, creating and establishing this community-based channel of science dissemination and advocacy, postulating solutions towards a more sustainable society.

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Challenges in Sustainability

Research Article

Reversing the Trend of Large Scale and Centralization in Manufacturing: The Case of Distributed Manufacturing of Customizable 3-D-Printable Self-Adjustable Glasses

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Abstract: Although the trend in manufacturing has been towards centralization to leverage economies of scale, the recent rapid technical development of open-source 3-D printers enables low-cost distributed bespoke production. This paper explores the potential advantages of a distributed manufacturing model of high-value products by investigating the application of 3-D printing to self-refraction eyeglasses. A series of parametric 3-D printable designs is developed, fabricated and tested to overcome limitations identified with mass-manufactured self-correcting eyeglasses designed for the developing world's poor. By utilizing 3-D printable self-adjustable glasses, communities not only gain access to far more diversity in product design, as the glasses can be customized for the individual, but 3-D printing also offers the potential for significant cost reductions. The results show that distributed manufacturing with open-source 3-D printing can empower developing world communities through the ability to print less expensive and customized self-adjusting eyeglasses. This offers the potential to displace both centrally manufactured conventional and self-adjusting glasses while completely eliminating the costs of the conventional optics correction experience, including those of highly-trained optometrists and ophthalmologists and their associated equipment. Although, this study only analyzed a single product, it is clear that other products would benefit from the same approach in isolated regions of the developing world.

Keywords: additive layer manufacturing; development; distributed manufacturing; eye care; glasses; 3-D printing

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1. Introduction

The history of mass production predates the industrial revolution and was initially motivated by the need to equip large armies with standardized weapons, but by the end of the 19th century the production of large amounts of standardized products on assembly lines became widespread and central to economics [1–3]. The benefits of large-scale manufacturing (or flow production) are well established and include reduction in costs due to the economies of scale from: i) bulk purchasing of materials, supplies, and components through long-term contracts; ii) technological advantages of returns to scale in the production function, such as lower embodied energy during manufacturing of a given product because of scale; iii) favorable financing in terms of interest, access to capital and a variety of financial instruments; iv) marketing and v) increased specialization of employees and managers [4–6]. These advantages have created a general trend towards large-scale manufacturing in low-labor cost countries, especially for inexpensive plastic products [7,8].

Centralized and mass manufactured goods are often still unaffordable to remote communities of the developing world because of proportionally large distribution and transportation costs [9]. These transportation costs have a concomitant embodied energy and environmental impact of transportation that can be substantial [10]. Centralized manufacturing, thus is deficient in two fronts; cost in the developing world and environmental impact. A sustainable manufacturing system with optimized value calls for a broader and more holistic view than lowest unit cost of production and points to the potential for distributed manufacturing systems encompassing engineering-management aspects, economic and technical issues, environmental drivers and social implications [11,12]. Until recently there was no technology capable of providing the necessary low costs and the ability to be distributed to isolated regions.

3-D printing offers a novel form of localized and customized production and is an emerging 21st century innovation platform for promoting distributed manufacturing systems [13–18]. The technological development of additive manufacturing with 3-D printers has been substantial [15,16], which has benefited many industries; however, the costs of 3-D printers have historically been too high to be feasible for distributed or home-based manufacturing [19]. Recently, several open-source (OS) models of commercial rapid prototypes have been developed [19], which offer an alternative model of low-cost production. The most successful of these is the self-replicating rapid prototype (RepRap), which can be built from 3-D printed parts, open-source electronics, and common hardware for about $500 [20,21]. Using computer aided design (CAD) customized (shapes and designs) prototypes can be produced quickly and economically [22] and there is evidence the RepRap can fabricate products less expensively than conventional manufacturing [23]. Distributed manufacturing using low-cost open-source 3-D printers has been shown to generally have the potential of reducing the environmental impact, in particular for plastic products [14–17,24] as the nature of 3-D printing allows for the minimization of production waste while maximizing material utilization [19,25,26]. Furthermore, distributed manufacturing in the form of open-source appropriate 3-D printing technology, combined with distributed generation (solar photovoltaic powered 3-D printers), has the potential to alleviate poverty in impoverished rural communities in the developing world [18].

This paper explores the potential advantages of a distributed manufacturing model of high-value products by investigating eyeglasses, which are currently only mass-manufactured for the reasons detailed above. Specifically, this paper reports on a case study of 3-D printable self-adjustable glasses by first reviewing the potential market for low-cost corrective glasses and then the limitations of centrally mass-manufactured self-adjustable glasses. Then a series of parametric 3-D printable designs is developed to overcome each of the identified limitations as a proof of concept. The results are analyzed for this case study and conclusions are drawn about the potential reversal of the manufacturing trend of centralization.

2. Case Study

The World Health Organization (WHO) estimates that globally about 314 million people are visually impaired, of whom 45 million are blind [27]. The WHO predicts that 80% of all visual impairment is avoidable (can be prevented or cured). The global distribution of avoidable blindness based on the population in each of the WHO regions is: South East Asian 28%, Western Pacific 26%, African 16.6%, Eastern Mediterranean 10%, American 9.6%, and European 9.6% [27]. With almost 90% of blind and visually impaired people living in low- and middle-income countries, including some of the world's poorest communities, access to eye care is often unavailable [27,28]. Globally 153 million people over 5 years of age are visually impaired as a result of uncorrected refractive errors (URE) [29].

Conventional approaches to correcting URE are firmly rooted in the health-care sector and involve having an eye care professional perform an eye examination to determine the general health of the eye and whether eyeglasses are required to improve vision [30]. Correcting URE requires both specialized complex equipment and professional eye specialists—ophthalmologists, optometrists/refractionists and opticians—to implement effectively. However, access to eye care and hence eyeglasses is severely limited in the developing world due to an acute lack of professionals and financial resources to provide adequate eye care services. For some cases in Africa: South Africa has approximately 2400 eye care practitioners servicing a population of roughly 47 million people [30] a ratio of approximately 1:20,000 whilst in Ghana the ratio of trained eye care professionals to members of the public is 1:200,000 [31,32] and approximately 1:1,000,000 for the case of Ethiopia [30]. These ratios are far less than the WHO recommended standard for 2010 of one refractionist per 100,000 population [27]. The African WHO region with 70.5 million estimated cases of vision impairment due to uncorrected refraction errors have a total of 4,985 existing functional clinical refractionist and thus requires an additional 10,138 [33]. Similarly, the South-east Asia region (196.2 million visual impairment cases) has 12,415 existing functional refractionist requiring an additional 21,651 [33]. Using a conventional approach this would require over $2,000 million for training the additional personnel and establishing new refraction care facilities over a 5 year period in Africa, and over $3,450 million for South-east Asia for the same period of time [33]. A full functional practice requires clinical refractive equipment, ocular health screening equipment, ophthalmic dispensing equipment and accounting and business equipment as well as the cost of start-up stock [33]. The Digital Refraction Systems alone can cost well in excess of $33,000 and ophthalmic dispensing equipment prices can be well over $10,000 [34]. Therefore, to establish a facility with basic equipment can cost over $100,000. Automated refraction requires access to expensive machines, which must be adequately maintained and calibrated and are mostly unsuitable for remote off-the grid communities and hence not a viable option. The ratio of ready-made to custom-made spectacles can be assumed to be 20 to 80, which is in line with expectations in the developed world [33,35]. Current market prices for ready-made prescription eyeglasses range from less than $7 online to over $1,000 from the optometrist [36]. This eyeglass price is currently beyond the budget of many developing world communities whose cost of living is less than a $1.25 per day. According to the World Bank report, more than 1.22 billion people in the developing world are living below this extreme poverty baseline [37].

The general steps in the provision of refraction services [27] can be summarized as in Figure 1.

A potential solution to this problem is self-refraction through the use of Silver's revolutionary self-adaptive eyeglasses [38,39]. Adjustable eyeglasses (Adspec lens/glasses) offer the user the ability to change the power of each adaptive lens independently to improve vision in each eye: a process known as self-refraction, a potential solution to the shortfall in eye care professionals in developing countries. Self-adjusting eye glasses thus provide a means of both measuring and correcting refractive error in regions underserved by eye care professionals. The use of wearer adjustable eyeglasses solves two problems: first, it reduces the need for measurement by a trained refractionist, which is crucial for regions with few eye care professionals. Secondly, it offers a much simpler and far cheaper deployment compared to a more conventional approach based on lens grinding or stock optics [30,38–42]. Self-adjusting eyeglasses would make vision correction accessible particularly to those in the developing world where there is either a lack of professionally trained optometrists and ophthalmologists, or where the cost of traditional spectacle lenses and professional consultation is prohibitively expensive [42].

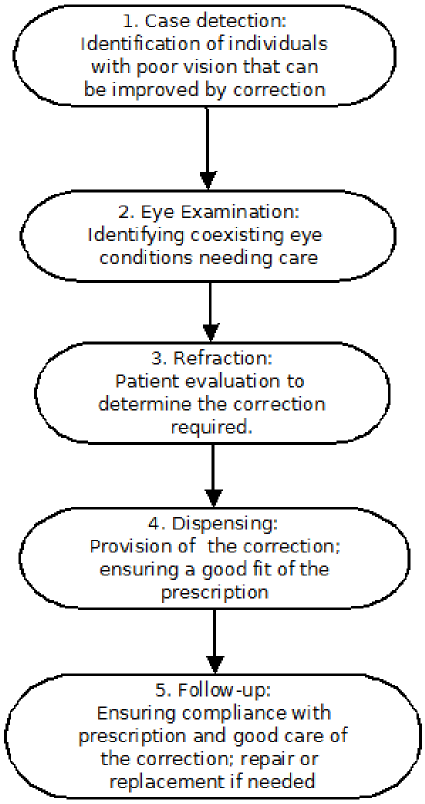

Figure 1. The general steps in the provision of refraction service.

The Adspec lens is composed of two thin circular membranes sealed at the edges and filled with a fluid with an index of refraction, *n,* of 1.579 [42]. The optical power of the lens is a function of the surface curvature, which is determined by the volume of the fluid in between the membranes. Hence by varying the fluid volume, the optical power of the lens can also be varied to the desired value. Mounting two adaptive lens on a specialized spectacle frame results in an adaptive spectacles (Adspecs) [42], which offers the user to ability to adjust the refractive power of each lens to achieve self-refraction. The useful power range of the lenses was reported to be −6 D to +12 D [42]. Preliminary field trials to determine the effectiveness of the Adspec lenses as a means of vision correction were performed both in selected African and Asian countries with promising results [38–43]. Vision correction using self-adjusting spectacles can be summarized as in Figure 2.

Adspecs have the potential for achieving Vision 2020; a partnership between the World Health Organization (WHO) and the International Agency for the Prevention of Blindness (IAPB) launched in 1999 with the twin aims of eliminating avoidable blindness by the year 2020 and preventing the projected doubling of avoidable visual impairment between 1990 and 2020 [27,28]. Adspec technology can be considered a great success, however, the deployed Adspecs have four remaining challenges: 1) the frame is highly fragile, which makes it potentially inappropriate for children and adults whose job involves manual labor (see Figure 3), 2) the costs are too high for target communities with low incomes, 3) people of different age, gender, ethnicity and geographical locations have variable widths between their eyes, which does not allow a one-size-fits all mass manufacturing of Adspecs, and 4) they are not aesthetically appealing and socially acceptable for many teenagers (i.e. they are not cool). The first generation of Adspecs tended to break at the hinge and users would use duct tape to make them operational as seen in Figure 3a and 3b, which did not assist with aesthetics and long term use.

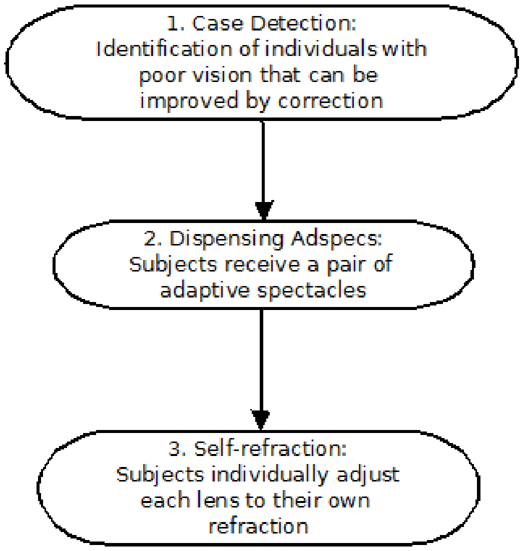

Figure 2. Adaptive spectacles self-refracting procedure.

Figure 3. a) Detail of hinge break on an Adspec lense and b) the Adspec system fixed with duct tape.

The use of open source appropriate techniques (OSAT) [44] such as open source 3-D printing has the potential to solve all four challenges. The first problem can be easily overcome by varying the thickness, printing density or combining different materials to achieve the desired strength at the hinge. Second, cost reductions of up-to 95% have been demonstrated for the open source 3-D printing of optics equipment [45] and the 3-D printing of common household products has been shown to be substantially lower than mass manufacturing retail costs, neglecting additional shipping and tax charges [23]. One major advantage of distributed fabrication is the ability to customize the products to meet specific individuals' or groups' needs. Customization provides the flexibility to selectively fabricate eyeglass frames to each individual's taste and eye spacing making the self-adjusting spectacles both appealing and comfortable to wear, solving challenges 3 and 4. Youth can be afforded an opportunity to design their own eyeglass frames according to their preferred shape, decoration and color. The experiments described below aim to provide a proof of concept for overcoming these four challenges with open-source distributed manufacturing.

3. Experimental

The entire software and hardware tool chain for the design and fabrication of the glasses used open-source technology, starting with a desktop computer running Debian 7.1 (http://www.debian.org). The glasses were designed using OpenSCAD 2013.06 [46], which is a free open-source CAD scripting program that generates and manipulates 3D objects. The glasses were designed to be parametric by declaring variables and then using them throughout the code. To make changes in the design (e.g. head width), the relevant variable is changed and the entire design is scaled immediately and can be exported as a 3-D model in the form of a .STL file. These files are sliced using Cura 13.06 [47], an open-source slicing program that converts the 3-D model into g-code. Finally, the g-code is then printed using the open-source Repetier-Host Linux 0.90C [48] printer controller. The glasses were printed in polylactic acid (PLA) on a MOST version of the open-source RepRap Prusa Mendel [49]. This version of the RepRap uses a Bowden extruder mounted to a J-head to increase print speed. The J-head takes filament and heats it to its glass temperature, extrudes it onto blue painter's tape to form a shape, and then is moved up two hundred microns to deposit the next layer of the design. In this way, the glasses are able to be printed in under an hour and can be customized both in design, color, fill density and to fit each person based on head width and the distance between pupils.

4. Results

The results of the three case study designs are shown in Figures 4, 5 and 6. Figure 4 a) displays the 3-D design and b) a digital photograph of self-refractive glasses using the Adspec lenses with the first generation syringe system. The new design and community printing capability allows for users to choose the preferred color of their glasses, to mix colors within parts or print parts of different colors, and to customize parts of the designs while in the community, as shown in Figure 4b.

In order to reduce cost further while improving aesthetics the external syringes can be replaced by a tube and pump system so that individuals can still adjust the lens after the initial screening. These tubes can be printed and personalized as shown in Figure 5 a) the 3D design, b) details the customized version of printed glasses. This design maintains the advantage of being able to adjust the glasses as light conditions or eye fatigue of the user change throughout the day. This ability to make dynamic adjustments, however, comes at the aesthetic cost of maintaining a fluid reservoir on the wearer's glasses. Although it should be noted it is possible to have a detachable reservoir.

There is a significant aesthetic challenge of designing glasses to fit perfectly circular lenses. To overcome this challenge at the expense of the continual adjustments, the glasses were redesigned to allow for one adjustment and then remove the syringe. In addition, using this scheme, as can be seen in Figure 6a it is possible to print goggles that fit the standard lenses. This approach may not be socially acceptable in all communities, but it provides distinct functional advantages in areas prone to dust or sand storms. This design is shown in Figure 6a, image in 6b.

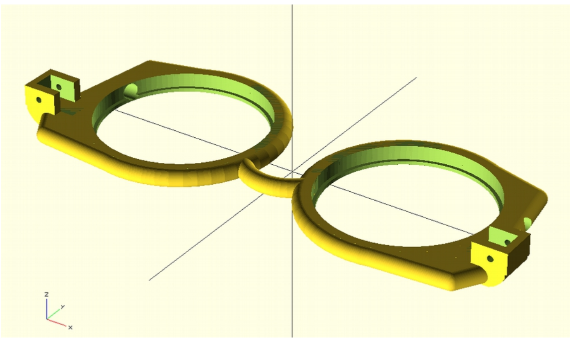


Figure 4. a) 3-D design of self-refractive glasses using the Adspec lenses and first generation syringe system, b) digital photograph of the design which has a customizable component (e.g. color choice of the user).

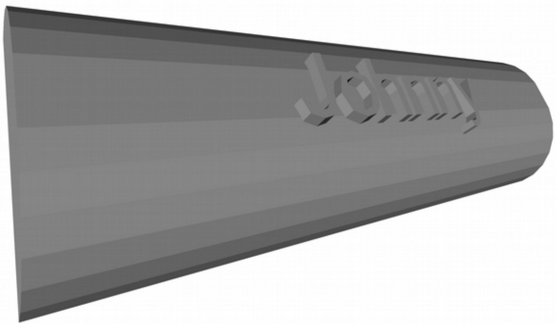

Figure 5. a) 3-D design of self-refractive glasses using a tube and peristaltic pump with standard Adspec lenses, b) digital photograph of the customizable component of the design.

All of the designs in Figures 4–6 are developed in OpenSCAD in a fully parametric manner so they can be used with the Thingiverse Customizer Application. This enables user/designers to custom fit the glasses for themselves, as well as choose personalized aesthetically pleasing extras to be printed into their glasses without the necessity to understand CAD. The Customizer interface is shown in Figure 7. As can be seen in Figure 7a, user/designers can set measurements specific to themselves, such as head width and distance between pupils. In addition, as can be seen in Figure 7b all of the other parameters, such as the stem length, width, thickness and dimensions around the hinge can be adjusted to meet user preferences.

The material costs for the 3-D printable designs shown in Figure 4–6 are shown in Table 1. As can be seen in Table 1 both the goggles and the standard glasses without the syringe can be printed in under 1 hour for about one U.S. dollar using conventional commercialized filament and U.S. electricity costs.

Figure 6. a) 3-D design of self-refractive goggles using a removable syringe clip system with standard Adspec lenses, b) digital photograph of the design.

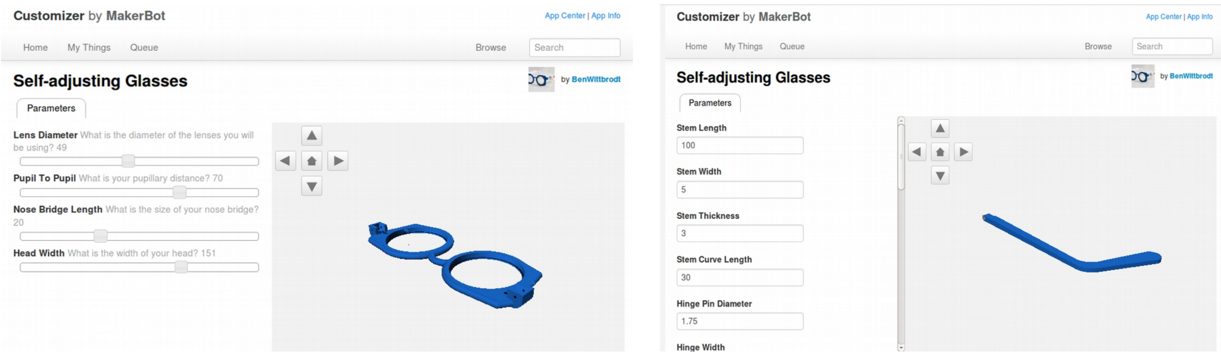

Figure 7. Screenshot of thingiverse customizer application used for customizing the 3D printable self-adjusting lenses glasses for a) the front of the glasses and b) the stems.

Table 1. Mass, print time, polymer costs, and total cost of 3-D printable designs using commercial filament and standard printing procedures [23].

Part	Mass (g)	Print Time (min)	Cost of plastic ($35/kg)	Total Cost including electricity at US ave. rates
Lens holders	15.82	28	$0.55	$0.57
Stem (each)	5.86	9	$0.21	$0.22
Stem with syringe (each)	24.17	37	$0.85	$0.88
Goggles	29.94	53	$1.05	$1.08
Glasses	27.54	46	$0.97	$1.00
Glasses with syringe	64.16	102	$2.25	$2.32

5. Discussion

The technical evolution of the self-adjustable lenses has progressed quickly, improving the quality while reducing the cost and scaling distribution. The new version of the Adspecs [50], which is being mass-manufactured and distributed now, is both more aesthetically pleasing and solves some of the technical deficiencies of the first generation shown in Figure 3.

5.1. Economic Costs

Cost is still the primary impediment to further scaling and complete saturation of the need for the glasses in the developing world. The results presented in this study show that distributed manufacturing of some of the components of the glasses with 3-D printers could further assist achieving Vision 2020, as they enable individual customizable components at the local scale at a lower price making the self-adjusting glasses potentially affordable to those living in poverty. Utilizing distributed 3-D printing will also allow for rapid replacement of failed parts, since any part can be produced in under an hour. Currently, a part would need to be ordered and time would be lost waiting for a replacement and a potential added cost in shipping of the new part. Using distributed 3D printing methods also offers greater flexibility in the choice of materials with desired properties and characteristics on the individual scale. The flexibility of open-source 3-D printers in materials selection also offers the potential to reduce the costs further. As can be seen in Table 1 the primary cost is that of the plastic commercial filament. Open-source hardware called 'Recyclebots' has already demonstrated that waste plastic can be converted into usable 3-D printing filament at a cost of $0.10/kg in electricity at U.S. utility rates [51]. Filament costs used in Table 1 were the average of $35/kg. Thus, this approach has the potential to reduce the costs shown in Table 1 to under a single U.S. penny for any design, essentially overcoming the cost barrier and making distributed production far less expensive than centralized manufacturing.

5.2. Limitations of the Approach

There are, however, several limitations to the proposed technology. This approach is currently limited by the state of development of open-source 3-D printing. Although RepRaps have been shown to print in a variety of materials, including metal [52], they are still not yet able to print the lenses (the most critical component of the eyeglasses) themselves. Further technical work is thus needed to be able to print all parts of the self-refraction glasses including the optics, as opposed to current prototypes in which only the frames and syringe are printed.

Although cost is a crucial part of the equation for full utilization, aesthetics is another challenge that should not be overlooked. In this regard, further work is needed to make printable, more aesthetically pleasing or 'cool' glasses. It is hypothesized that having students help in the design of their own glasses will help assist in this cool-factor, but that hypothesis must be tested by experiment.

Further work is needed in optics and 3-D printing to be able to overcome the current limitation of the need for circular lenses. The ability to vary lens shape and size will make it less challenging to meet the temporary, geographical and clique shifting socially-acceptable requirements determined by the world's teenagers. Finally, community capacity development and skills appraisal workshops could assist in providing for the sustainability of the community-run/owned 3-D printing facilities.

5.3. Sustainability of Distributed Manufacturing

Although the environmental damage caused by the manufacturing of glasses is relatively small compared to other manufacturing sectors, this work provides a model for improving the sustainability of manufacturing not only of glasses, but also other products. Recent studies have shown a number of benefits that can be derived from adopting 3-D printing technologies, in particular environmental benefits [24]. The previous study showed that with RepRap printing using solar photovoltaic power the distributed manufacturing always has a lower environmental impact as compared to conventional manufacturing of polymer products [24]. Prototypes of solar powered 3-D printing systems have already been demonstrated for semi-mobile school-based systems, and a highly-mobile system capable of fitting in a suitcase [53]. The latter system could be used to provide the glasses solution to any rural school which can be accessed by travelers bringing standard luggage. The former design is meant to become a permanent fixture at rural schools that are not connected to the electrical grid. Thus, the solar-powered 3-D printer can be used first to provide glasses for the students and other community members that need them, and then it can be used to manufacture other high-value products, such as scientific tools (for both education and use in, for example, medical clinics) [54]. In all these cases any products would have a lower environmental impact than conventionally manufactured products, even if made locally. Realistically, most specialized products would be manufactured in a centralized facility far from the users and the embodied energy of transportation would be substantial [55]. Thus, solar-powered distributed manufacturing allows off-grid rural communities to leapfrog to a more sustainable method of production. For on-grid communities using the same source of electric power, if the fill density of the 3-D printed plastic product is below 79% fill density then the environmental impact of the 3-D printed object remains lower than conventionally manufactured goods [53]. Some of the components to the glasses do not need to be printed at 100% fill to maintain mechanical integrity and would thus offer this sustainability benefit as well. Many consumer products can be printed for less than 20% fill density [23], thus significantly improving sustainability for any of the RepRap 3-D printers used at the schools to fabricate other products.

However, there is a lack of data on long term field performance of 3-D printed products. The finished products need to undergo field evaluation for both ruggedness and social acceptability by selected representative samples mainly from the developing world communities. Results from the field tests may be used to further improve the 3-D designs for this project. In addition, this data could be used to perform a complete life cycle analysis of the products and compared to conventionally-manufactured products. The stability and life-time of the materials used need to be documented and the recycling plan of old and disused products be put in place within communities. Again, just as the Recyclebot technology [51] would significantly improve the economics, it would have a similar positive effect on the environmental impact [56]. Thus, broken or simply old glasses could be ground up and turned back into 3-D printer filament to be turned back into glasses or other products.

5.4. Lateral Scaling

The feasibility of the approach to reach a large scale and thus millions of people all over the world is dependent on what Rifkin calls lateral scaling [57]. In this model of production and distribution, schools all over the developing world will operate a RepRap 3-D printer in relative isolation with no centralized management or logistics. The construction and maintenance of RepRap printers has been demonstrated by amateurs thousands of times all over the world. Specifically, in the U.S., teachers are trained to build and maintain RepRaps in training workshops. A team of two inexperienced teachers can build a delta style RepRap printer in a day. As a true RepRap, this printer could then be used to manufacture the specialized plastic components of both itself and other printers to spread the technology throughout the region. This model could be adopted in the developing world at very low cost points, as the RepRap knowledge materials (for constructing, maintaining and printing) are all available for free on line.

The data in Table 1 can be used to evaluate what this would look like in an individual school or community with a single RepRap, which costs less than US$500 in parts, all of which are available for purchase on the Internet. With either the glasses or goggles using approximately 30g of plastic a single US$35 kg spool of filament would be able to correct the vision of 33 children. If the syringes were printed as well this would be only 15 children per kg spool. Again, as mentioned above, if the spools were Recyclebot plastic, the costs would be less than $0.01 per student served. To continue to operate the printer, the school would need access to either the purchase of plastic online or locally or the ability to turn waste plastic into filament. The staff to operate the printer could be trained in workshops or learn online for free. Ideally, the students themselves would learn to operate and maintain the printers as part of their education. If the 3-D printer at a school was staffed 8 hours per day and was only used to make glasses it could produce 8 pairs per day or 5 pairs with the syringes per day (note: that the final print of the day can be set up and left unattended thus effectively increasing printing time beyond 8 hours/day). Thus, roughly 1kg of plastic would be consumed per school week of continuous production of glasses. Thus, if operated for an entire year only printing glasses, a single RepRap could produce 2,080 pairs of glasses and Sconsume about 52 kg of plastic.

The primary application of this solution would involve base design code (e.g the OpenSCAD scripts) being untethered from the web and transported manually with the 3-D printer along with the necessary plastic to provide glasses given a school's population. Thus, only the imagination of the student population and electricity would need to be supplied. In the case of electricity this would be provided on site either from the grid, generators, batteries or the previously discussed solar panels, depending on the community's circumstances. This is a start, however, in many locations now and in a growing number of developing world communities, Internet access will enable more sophisticated and rapid design browsing and cloud-based design could play a greater role. Cloud manufacturing, is a service oriented, customer centric, demand driven manufacturing model [58]. It could be used by entrepreneurs in developing world communities (e.g. to collaborate on designs, provide design services for sale, and even perhaps to manufacture items for sale in both their communities and elsewhere [59,60]). Again, in the ideal case, these revenue streams could provide a return on the investment of the initial capital needed for the RepRap, Recyclebot and filament to get started, and provide the necessary vision correction with self-refraction eyeglasses for students and local residents. The additional technical skills in the community and the ability to manufacture low-volume high-value products in an environmentally sustainable way would be a significant benefit. The technology discussed here is only a single example of how open-source 3-D printers could provide high-value products to communities in the developing world at very little cost as there have been many proposals for other appropriate technologies and scientific tools [18,53].

6. Conclusions

Although the trend in manufacturing has been towards centralization, the technical development of the open-source 3-D printer enables low-cost distributed bespoke production. This paper demonstrated some of the potential advantages of a distributed manufacturing model of high-value products by investigating self-refraction eyeglasses. By utilizing 3-D printable self-adjustable glasses the target market not only gains access to far more diversity in product design, but also offers the potential for significant costs reductions for obtaining functional corrective glasses. The results showed that the primary cost of the glasses could be reduced to about one dollar for a highly customized/individualized design, which could be printed on site in under an hour. Distributed manufacturing with 3-D printing can empower these communities through the ability to print less expensive and customized self-adjusting eyeglasses, displacing conventional glasses and giving a viable option to the world's most impoverished population who generally cannot afford the cost of expert optics correction (e.g. optometrist, ophthalmologist, or even conventional lenses). Here only a single product was analyzed, but it seems clear that other products would benefit from the same approach and that distributed manufacturing can assist in sustainable development, particularly in isolated rural regions.

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