PRODUCT MANUFACTURING: TRADE-OFFS, CHALLENGES, AND STRATEGIES

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Abstract

Many academics take a technocentric approach to development. It is easy to believe in the nascent stages of a project that strong design and a low price point will lead to widespread impact. However, technology design is only one aspect of a venture. Throughout the development-engineering sector, there is lack of emphasis on implementation strategy, rendering innovators incapable of transitioning their products and ventures from the confines of academia to the real world. Manufacturing products at scale proves to be a major challenge in bringing products to market. Often it is difficult to know what manufacturing options are available and most appropriate for a given venture: Should designs change so manufacturing can occur locally? Should manufacturing happen in the US or China or the country of sale? Should inexpensive products be prioritized over low environmental costs? This paper illuminates tradeoffs apparent in the manufacturing phase of development engineering. It further provides a framework of factors for designers to consider when evolving their ideas into scalable products.

Introduction

Approximately 2.2 billion people throughout the world live on less than 2 USD per day (World Bank 2014). Challenges faced by impoverished populations result from food system vulnerability, nonexistent formal infrastructure, and nonfunctional healthcare systems, among many others. Multilateral institutions, non-governmental organizations (NGOs), private sector companies, and academic institutions each utilize different strategies to improve aspects of life in emerging countries such as large-scale investments, conditional-cash transfers, donated goods, and entrepreneurial ventures. The success of these solutions depends greatly on the structural, operational, and financial barriers that exist in each context.

Across Europe and the United States, multiple university programs have grown out of traditional design programs and focused on altering Dr. Paul Polak's famed statistic that "The majority of the world's designers focus all their efforts on developing products and services exclusively for the richest 10% of the world's customers. Nothing less than a revolution in design is needed to reach the other 90%." In the past decade, technology solutions have been lauded as a primary mechanism of change in developing countries. Appropriate technologies exist in nearly every sector and at every price point, including a $2,000 car (Prahalad 2012), $200 water pumps, $20 cell phones, and $0.25 diabetes test strips. However, while these designs for the other 90% are beginning to happen, few products have had significant impact. Despite well-intentioned prototype testing in emerging markets, the majority of products fail to reach the commercialization stage (Donaldson 2008). Many factors influence commercialization for agricultural technology ventures including access to capital, supply chain reliability, customer needs, and product characteristics (Suffian et al. 2013). Although decisions around product manufacturing greatly affect commercialization, they are often considered late in a design process or after the creation of high-fidelity prototypes.

The design processes taught instead focus on the creation of prototypes, with little emphasis on systems-thinking approaches. Professors and practitioners alike have modified the process shown in Figure 1 numerous times to serve different academic and situational purposes.

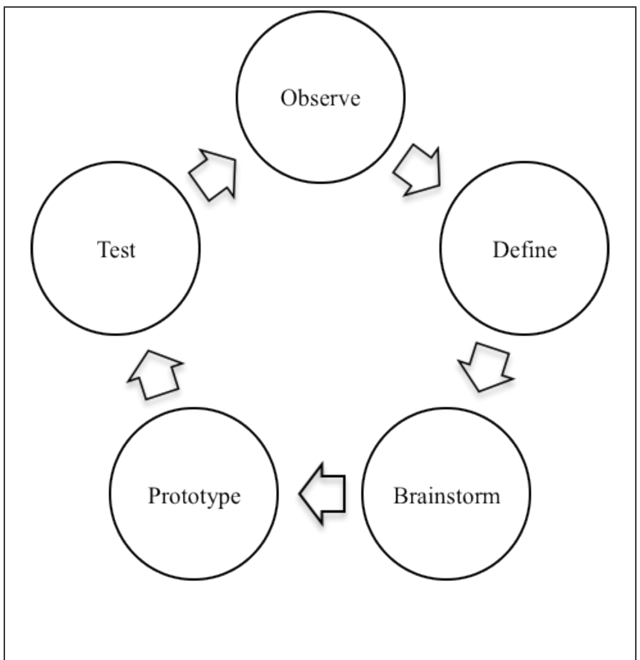

Figure 1. Iterative Design Process

Iterative design processes excel at alerting designers about the need to revisit assumptions and adjust features to fit user needs. Unfortunately, iterative design processes fail to draw connections between prototypes and possible avenues of scale. While design for manufacturability guidelines have long been established (Boothroyd 1994), they are not always integrated into the traditional design process. These process maps allow students to consider product use, but ignore how the products will be manufactured, what resources are required, and how material sourcing might influence the final cost.

When creating products intended for use in emerging markets, affordability often drives design. However, the final cost to a consumer is determined by the entire system of a product – the transportation, tariffs, and marketing costs – and not just the production rate. Thus, it is critical that manufacturing be considered early in the design phase. Design for manufacturability prompts designers to think about material selection, component parts, and time to market, as well as disassembly procedures and the product's end-of-life (Hermann et al. 2004).

By viewing product design as a system rather than a process, the importance of manufacturing becomes rapidly apparent. The design process shown in Figure 2, adapted from Philip Koopman, shows product design and the manufacturing process as parallel and interdependent steps (Koopman

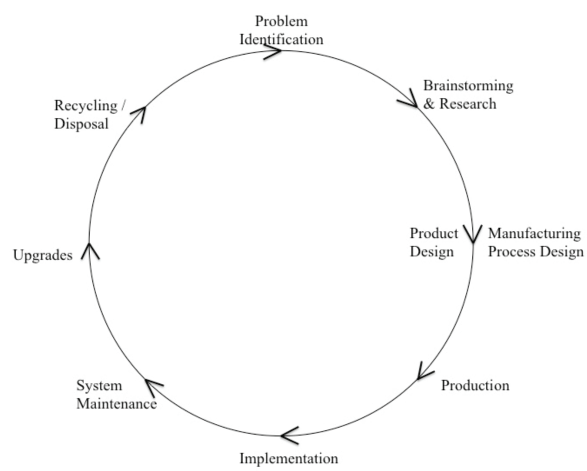

Figure 2. Manufacturing Product Design

1998). For example, imagine an innovator is working to create a spirometer to measure the lung capacity of individuals with upper respiratory infections. The problem definition phase revealed that removable mouthpieces are needed to prevent disease spread. It would be necessary to consider how to design the mouthpieces so that they can be easily manufactured and shipped in a sanitary way, ensuring that they reach the consumer in sterile condition. Further, it would be important to consider how multiple component parts might increase the device's price point, and how to standardize the mouthpieces so that they are guaranteed to fit properly into the device.

Product manufacturing is an immediate precursor to the implementation of a venture. In some cases, the manufacturing facilities and end users are in different locations. Multiple challenges arise regarding the development of a successful and sustainable supply chain. Failing to develop this supply chain can prevent ventures from "crossing the chasm" and becoming thriving entrepreneurial endeavors. In other cases where manufacturing is deliberately done close to the end users, issues of quality control and standardization across manufacturing plants may arise. However, many student entrepreneurs and development practitioners have little experience considering these cases that are necessary in order to manufacture products efficiently. This paper seeks to elucidate the decisions individuals must face when designing and manufacturing products for use in resource-constrained environments. It will additionally provide examples of challenges faced when manufacturing appropriate technologies. Finally, commonly utilized manufacturing strategies will be discussed along with their respective benefits and challenges.

Issues, Trade-offs, and Considerations

The manufacturing of appropriate technologies is a necessary step for entrepreneurs wishing to leverage a pilot into a mature venture. Decisions made around manufacturing dictate many social, technical, environmental, and financial facets of business operations. In the dynamic environments inherent to developing countries, changes and system shocks arise that influence a company's operations. However, entrepreneurs may mitigate chaos through decisions made during the design process. The following list delineates important manufacturing considerations for entrepreneurs, academics, and students. This list is not all-encompassing, but it is the hope of the authors that its factors will spark conversation regarding certain issues and challenges that directly or indirectly influence the relative success of a venture's manufacturing phase.

Technical

Material Selection

The materials that are used for the construction of a product impact final cost, usability, and lifespan. From a manufacturing perspective, material selection directs the required level of machining and processing. A vernacular material such as bamboo can be cut to size and used in a raw form. However, products that incorporate metal components lead to an array of manufacturing challenges. How are components adjoined? Should welding be employed? What strength of connection does the design require? How durable does the design aim to be?

Example: A team of innovators is deciding what materials to use to create the frame of a solar food dryer. Aluminum is inexpensive and easily processed, but prone to deformation. On the other hand, steel is expensive and difficult to work with. However, steel is extremely durable and can withstand stress induced by weather and the environment over time. Can users afford a higher upfront cost for a product that promises a longer lifespan?

Available Technology and Resources

A design's complexity will dictate the technologies and resources that must be available in order to conduct the necessary machining and processing. While machining technologies are often available in emerging market contexts, it is not a guarantee, and they are often less advanced. Thus it is often difficult to manufacture technologies in the location where distribution is intended. Further, once the manufacturing context is identified, one must also consider if a single manufacturer can perform all steps in the production.

Example: The design of a solar food dryer includes aluminum sheets to serve as thermal absorbers. The team has outlined a design requiring precise and detailed cuts to allow for air circulation and easy assembly, mandating the use of a water jet cutter. Thus, instead of manufacturing in the target context of Ethiopia, the metal sheets will need to be produced in India. An alternative solution would be to alter the design and either incorporate more standard sized and shaped sheets, or alter the cuts so that they could be accomplished through stamping.

Replacement Parts

A common reason development technologies fail is a lack of compatibility between the design environment and the intended use context. For example, in developing countries 95% of medical devices are imported and of those, close to 96% are no longer working after 3 years (Dzombak, Mehta, and Butler 2015). A lack of spare parts was identified as one major reason why devices fail (Malkin 2007). When creating a technology, designers need to consider what parts will need to be available in users' markets if and when the technology fails. If parts are not commercially available, how can a distribution system be designed to ensure replacement parts reach customers, given supply chain constraints?

Example: The solar food dryer design includes a sheet of plexiglass over the collection chamber. While plexiglass is the ideal material to allow for light permeation, once cracked it can cause sub-optimal airflow, as well as potentially allowing moisture seepage. Replacement plexiglass is difficult to find in large sizes in emerging markets. The team therefore must consider how they can add mechanisms such as rubber bumpers or offer recommendations on dryer storage to protect against glass breakage. They may also want to partner with regional manufacturers or invest in a storage facility that stockpiles spare sheets.

Maintenance

Though replacement parts may be available, users of a technology may not be trained to perform the necessary maintenance or repairs. How can the design be modified to ease maintenance for the target users? Will the technology require a specialized maintenance team? If all users are concentrated in a single area, a dedicated service team may prove financially viable. However, if users are spread throughout multiple regions, can the technology be manufactured with an intuitive repair process in mind?

Example: Often repair knowledge for a technology is contained within a densely worded user manual. Over time, manuals get misplaced or thrown out, leaving the user without any instructions on how to improve a technology. Consider instead, for the solar food dryer, if instructions were painted on to the side of the device. The incorporation of pictures would simplify the instructions for users, but could complicate the manufacturing process.

Social

Local vs. Global

An important decision that entrepreneurs need to make is whether to manufacture technologies locally or outsource. Local manufacturing benefits the community by providing jobs and economic stimulus. However, entrepreneurs must be realistic about manufacturing within resource-constrained communities, as a lack of necessary support infrastructure can lead to an increase in overall cost and a decrease in quality control (Patel, Maley, and Mehta 2014). Outsourcing can lead to efficient manufacturing operations, though extending supply chains can cause unpredictable challenges such as import regulations, increased tariffs, and increasingly complicated logistics.

Example: A team of innovators working on a solar food dryer decides to manufacture their technology in the same villages in which the dryer will be sold. The short, manageable supply chain enables increased transparency and brings economic gain to the community involved. However, the supply chain lacks robustness. The local markets run out of a critical material and do not know when the next shipment will arrive. Customers are lost because the dryers cannot be delivered according to planned schedules.

Employee Requirements

When deciding where to manufacture a product, it is important to consider the human capital necessary for operations. What skills must laborers possess? Who will manage daily processes? Despite high rates of unemployment in developing countries, a lack of trained workers can lead to low manufacturing productivity. This can significantly increase the manufacturing time compared to manufacturing in regions where higher-skilled workers are available.

Example: The solar food dryer team wants to make a version of the product available that includes sensors to monitor whether optimal drying conditions are achieved. This requires advanced features and electrical wiring that would prove unfamiliar to an unskilled worker. In order to guarantee high-quality production, utilizing Chinese manufacturing channels might prove more beneficial.

Worker Safety

Regardless of where manufacturing operations are located, worker safety is of critical importance to any company. In developing countries, regulations are often unenforceable as a result of corrupt government officials and a lack of national infrastructure. This makes it easier to exploit workers and subject them to undesirable conditions. If a company is not operating in the same region as its manufacturing operation, it can be difficult to know what labor practices are implemented during production. Mechanisms must be designed in order to ensure that transparency exists along the supply chain.

Example: A solar food drying manufacturing facility is set up in a rural area. Despite instructions by the venture to purchase worker gloves, employees are not provided with them and must use their bare hands. While hurriedly carrying the glass for a new solar dryer, a worker trips over debris and the glass breaks, cutting the worker's hand. If the manufacturing facilities are far from the venture's headquarters, random and unannounced auditing of the manufacturing process may be a necessary part of production.

Economic

Overhead Costs

Manufacturing costs encompass more than just capital investment in machines. Labor, materials, electricity, transportation, and rental costs all factor into the total cost of production. If electricity is unreliable, production efficiency will decrease, which will increase costs. If manufacturing ecosystems do not exist locally, the overhead costs may prove significantly high, as opposed to areas where resources can be shared between various firms.

Example: When attempting to source materials for the solar dryer, the team wants to find both material wholesalers and transporters locally so they can manufacture in close proximity to their user base. They find land space 30 km from the community they are working in and decide to try to establish operations there. The transportation company is unfamiliar with the proposed manufacturing location and therefore wants to charge a premium because they have no other stops in the area. The wholesalers nearby have 80% of the necessary materials and tell the team that they will have to import the remaining 20%. Should the team change their design to cater to what is locally available? Should they instead manufacture in a more established industrial center? What implications do these decisions have on the economic bottom line?

Standardization vs. Customization

Often consumers want to tailor aspects of a design to more directly meet their individual needs. While customization can lead to a highly satisfied customer, it can also raise product costs considerably because the company is no longer able to utilize economies of scale. Standardized products can contribute to highly efficient manufacturing operations; however, they may not appeal to a particular customer base. For example, the Jaipur Foot, a prosthetic foot manufactured in India, was previously customized for each amputee in need. The vulcanized rubber used to comprise the foot was heavy for users and hand-making each foot led to challenges with quality control. Therefore, the team behind the Jaipur foot began using injection-molded polyurethane in order to standardize manufacturing operations and increase the production phase. The polyurethane feet lack elasticity and are known to crack when users squat during defecation. Thus, despite improved manufacturing processes, design challenges persist (Creel 2013). What is more important to prioritize for a given company? How different are user requests and what do they depend on? Gender? Income? Personal preference?

Example: When testing the solar food dryers with different potential users, the team receives conflicting feedback regarding the size of the dryer. Some users say that the size is too big and contributes to the cost being prohibitively expensive. Other users say that the dryer is too small and does not offer sufficient drying capacity. The company considers customizing each dryer to meet user needs, but ultimately decides to offer three different versions. Though they still may not satisfy some niche consumer preferences, they ultimately want to appeal to a mass market.

Quality Control

Often when obtaining materials in developing countries, one can purchase several supposedly “standard” copies of the same product and end up with significant variations in size and quality. Manufacturing processes that employ significant human input and unskilled laborers are typically less precise when measuring and cutting materials. Minimizing the number of steps in the manufacturing process, as well as striving for a highly replicable design are two strategies to help control quality of a final product.

Example: When producing the solar food dryer frame, the team employs laborers to assemble multiple metal components. Because of skillset variability among the workers, the resulting products are of different quality, with some seeming sturdy and secure and others appearing to have loose connections. To rectify this, the team decides to eliminate worker input by utilizing pre-fabricated metal sheets the workers can instead bend into place.

Environmental

Embedded Waste

Ventures operating in resource-constrained environments must pay particular attention to minimizing waste. In these contexts, sufficient waste infrastructure does not exist and therefore practices such as uncontrolled incineration or smelting of electronic components are commonplace. These processes can prove extremely hazardous to worker health through the release of toxic emissions (Pacyna et al. 2010). Entrepreneurs should consider what waste elements are embedded within their supply chain and attempt to see how they can reuse or ensure safe disposal of such byproducts.

Example: During the production of the solar food dryer, the team decides to cut the metal sheets to the proper shape by punching, in order to facilitate the quick assembly of final products. However, punching produces large quantities of scrap metal. The scraps are small and cannot be incorporated into the design. How can the manufacturing process be altered to prevent this step? Could a different machining strategy be used to achieve the desired metal shape?

Environmental Impact

The emissions associated with a given product can vary greatly, depending on the energy sources utilized. If using photovoltaic (PV) cells or other forms of renewable energy, the emissions will be lower; however, the availability of power may prove variable due to a lack of storage, influencing the operation cycle time. If manufacturing in a country that uses coal as an energy source, the production will lead to higher levels of carbon released. The lifecycle energy input into a product is important to track because the long-term effects of climate change will be most intensified in developing countries.

Example: When deciding whether to manufacture locally or outsource, a team wants to assess the full environmental impact of their product. For resource extraction through decommissioning, they assess both the material and energy inputs for each stage of the production process. This reveals that the variability in the electricity in their target context will lead to significantly less efficient operations. Depending on the size of their operations, they could either invest in a PV system along with a backup generator, pay to offset the carbon emissions associated with outsourced manufacturing, or determine if a change in materials could help to lower the overall product energy input.

End-of-Life

A product may reach end-of-life because of functional obsolescence, product performance degradation, or technical obsolescence, when new products render the original technology useless. No matter the reason, every product will eventually lose its utility and be disposed. What is the assumed product lifespan? Can it be repurposed into a new product? Can it be easily taken apart? Will it have to be placed in a landfill? Can elements be recycled?

Example: When deciding on options for the transparent part of the solar dryer, a team considers either using a more durable, imported plexiglass or a locally available glass. While the plexiglass may increase the product lifespan, the local glass has more potential to be repurposed. How will users dispose of the product? What potential is there for reuse?

Strategies for Manufacturing

Many of the decisions faced during the manufacturing stage are connected to the underlying tension of local versus outsourced manufacturing operations. Ultimately, the decision of where to locate manufacturing operations requires analysis of company priorities, available resources, financial viability, and business transparency. Hybrid models that include outsourced and local operations exist and have been used successfully in bringing products to market while simultaneously creating economic stimulus within communities. The following section details three manufacturing strategies and contains examples of how such strategies have been employed in the past.

Local Product Model: Local Manufacturing + Local Assembly

Manufacturing locally can yield significant benefits to the community, but success hinges on the level of infrastructure that exists in the area where the venture is located. Some small-scale manufacturing infrastructure could be available and offered by local universities or technology institutions. For example, Gearbox, a makerspace in Nairobi, provides tools and equipment for fabrication, electronic building, and rapid prototyping (Gearbox 2015). Gearbox provides the opportunity for individuals to move from concepts to prototypes to final products, but is not intended for manufacturing at scale. There has been a recent surge in the availability of 3D printers throughout emerging markets. If 3D printers are available, they can assist in the manufacture of products with minimal waste. Printers require the availability of printing materials and electricity that are frequently unavailable in resource-constrained contexts. Local manufacturing can succeed if it is possible to leverage an informal labor market for manufacturing operations, such as jua kalis in Kenya. Rather than create single manufacturing facilities, these independent machinists can be contracted to construct products in batches. This would allow for more geospatially distributed product availability, which could improve resilience to certain local externalities such as power outages or weather-related transport issues.

BENEFITS	CONSIDERATIONS
• Community economic benefit • Job creation • Low transportation costs • Manageable supply chain • Lower tariffs	• Availability of necessary resources • Skill of labor pool • Electricity reliability • Quality control • Regulation • Overhead costs

Hybrid Model: Outsource Manufacturing + Local Assembly

Hybrid manufacturing models serve to effectively leverage available community resources while also reaping the benefits of an integrated global supply chain. For example, after struggling to have the stoves fully manufactured in Darfur due to a lack of materials and equipment, the team behind a low-cost cookstove decided to shift their manufacturing operations to India. The design for the stove is now stamped onto metal sheets for India and then, along with supplemental materials, shipped as flat kits to Sudan. Once in Sudan, trained workers can follow guides on the metal sheets to assemble the stoves without advanced tools and prepare them for distribution (Gadgil, Sosler, and Stein 2013). This strategy constrains the design because it requires minimal assembly once on site. For example, the team wanted to include a latched door because it increases the efficiency of the stove; however, the moving part would decrease the durability of the design (Amrose et al. 2008).

BENEFITS	CONSIDERATIONS
• Use of local labor • Job creation • High quality control • Manufacturing efficiency • Fast cycle time	• Disparate supply chain • Lack of oversight • Import tariffs

Import Model: Outsource Manufacturing + Outsource Assembly

If working in an area with minimal infrastructure and resources, outsourcing both manufacturing and assembly may prove to be the only viable option. If a majority of the raw materials for a product are not locally available, the benefits of local manufacturing may be outweighed by the added complexity of the manufacturing supply chain. For example, while cell phones and related technologies are widely used even in the most rural environments, it is not feasible to create local manufacturing or assembly facilities with the same degree of standardization or quality control as found in Chinese companies. Importing is also a useful strategy for technically sophisticated products. For example, medical devices with intricate electronic components require manufacturing to be performed with specialized equipment that can achieve high degrees of precision or can maintain a sterile environment.

BENEFITS	CONSIDERATIONS
• High quality control • Manufacturing efficiency • Fast cycle time • Less expensive production	• Disparate supply chain • Lack of oversight • Import tariffs

Conclusion

The manufacturing and processing needs for a venture depend on product type, company scale, available resources, and priorities. Regardless of the complexities involved in creating a sustainable manufacturing strategy, these considerations must be woven into the initial design process in order to ensure that technologies will fit into a larger venture ecosystem. Failure to think systemically during the design phase can lead to significant implementation barriers. Consequently, the proper use of these considerations in design will allow ventures to "cross the chasm" and evolve their ideas into sustainable, scalable products.

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References

Amrose, S., G. T. Kisch, C. Kirubi, J. Woo, and A. Gadgil. 2008. "Development and Testing of the Berkeley Darfur Stove." Lawrence Berkeley National Laboratory.

Boothroyd, G. "Product Design for Manufacture and Assembly." 1994. Computer-Aided Design 26(7): 505-520.

Creel, J. 2013. "The Jaipur Foot Redesign: Making a Great Prosthetic Foot Even Better." Engineering for Change. Accessed December 20, 2014. https://www.engineeringforchange.org/news/2013/05/09/the_jaipur_foot_redesign_making_a_great_prosthetic_foot_even_better.html.

Donaldson, K. 2008. "Why to be Wary of 'Design for Developing Countries'." Ambidextrous 1(98): 35-37.

Dzombak, R., K. Mehta, and P. Butler. 2015. "An Example-Centric Tool for Context-Driven Design of Biomedical Devices." Advances in Engineering Education. In press.

Gadgil, A., A. Sosler, and D. Stein. 2013. "Stove Solutions: Improving Health, Safety, and the Environment in Darfur with Fuel-Efficient Cookstoves." Solutions 4. http://www.resilience.org/stories/2013-03-27/stove-solutions-improving-health-safety-and-the-environment-in-darfur-with-fuel-efficient-cookstoves.

Gearbox. What We Offer. 2015. Accessed December 20, 2014. http://gearbox.co.ke/what-we-offer.

Hermann, J. W., et al. 2004. "New Directions in Design for Manufacturing." ASME 2004 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers. 853-861.

Koopman, Philip. 1998. "Using CAD Tools for Embedded System: Obstacles Encountered in an Automotive Case Study." *Integrated Computer-Aided Engineering* 5(1): 85-94.

Malkin, R. A. 2007. "Design of Health Care Technologies for the Developing World." *Annual Review of Biomedical Engineering* 9: 567-587.

Pacyna, E. G., et al. 2010. "Global Emission of Mercury to the Atmosphere from Anthropogenic Sources in 2005 and Projections to 2020." *Atmospheric Environment* 44(20): 2487-2499.

Patel, S., S. Maley, and K. Mehta. 2014. "Appropriate Technologies in the Globalized World: FAQs." *IEEE Technology and Society* 33(1): 19-26.

Prahalad, C. K. 2012. "Bottom of the Pyramid as a Source of Breakthrough Innovations." *Journal of Product Innovation Management* 29(1): 6-12.

Suffian, S., A. De Reus, C. Eckard, A. Copely, and K. Mehta. 2013. "Agricultural Technology Commercialisation: Stakeholders, Business Models, and Abiotic Stressors–Part 2." *International Journal of Social Entrepreneurship and Innovation* 2(6): 561-577.

World Bank. *Poverty Overview*. 2014. Accessed December 20, 2014. http://www.worldbank.org/en/topic/poverty/overview.