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Methods and Metrics to Measure and Predict the Social Impact of Engineered Products

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Predict the Social Impact of

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ABSTRACT

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More than ever before, engineers are creating products for developing countries. One of the purposes of these products is to improve the consumer's quality of life. Currently, there is no established method of measuring the social impact of these types of products. As a result, engineers have used their own metrics to assess their product's impact, if at all. Some of the common metrics used include products sold and revenue, which measure the financial success of a product without recognizing the social successes or failures it might have. In this thesis I introduce a potential metric, the Product Impact Metric (PIM), which quantifies the impact a product has on impoverished individuals – especially those living in developing countries. It measures social impact broadly in five dimensions: health, education, standard of living, employment quality, and security. By measuring impact multidimensionally it captures both direct (having to do with the products main functions) and indirect impacts (not related to the products main functions), thereby revealing more about the products total impact than with other metrics. These indirect impacts can have a larger influence on the consumer than the direct impacts and are often left unmeasured. It is calculated based on 18 simple field measurements of the consumer. The Product Impact Metric can be used to predict social impact (using personas that represent real individuals) or measure social impact (using specific data from products introduced into the market).

Despite its challenges, the measurement of a program or policies social impact is a common practice in the field of social sciences. This measurement is made through social impact indicators which are used to measure, predict, and improve potential social impacts. While there are clear benefits to predicting the social impact of a product, it is unclear how engineers are to select social impact indicators and build predictive models. This thesis introduces a method of selecting social impact indicators and creating predictive social impact models that can help engineers predict and improve the social impact of their product. First, an engineer identifies the product's users, objectives, and requirements. Then, the social impact categories that are related to the product are determined. From each of these categories, the engineer selects several social impact indicators. Finally, models are created for each indicator to predict how a product will change these indicators. The impact categories and indicators can be translated into product requirements and performance measures that can be used in product development processes. This method of predicting social impact is used on the proposed, expanded U.S. Mexico border wall.

Keywords: Phillip Stevenson, Social Impact, Predictive Models, Product Design

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NOMENCLATURE

c_{Border}	Annual cost of the border.
$c_{\text{Off.}}$	Annual cost of a border patrol officer.
c_{Repair}	Typical cost of a border wall repair.
$k_{\text{Arr.}}$	Rate that illegal immigrants are arrested throughout the country.
$k_{\text{Arr. New}}$	Rate of change in the number of illegal immigrants that are arrested.
k_{Change}	Change in border crossing method factor.
k_{Cross}	Change in number attempting to cross the border factor.
$k_{\text{Off. Sec.}}$	Improved officer security factor.
k_{Replace}	Rate that border patrol officers are replaced by the border wall.
k_{Return}	Rate that illegal immigrants return to their countries.
$k_{\text{Sec.}}$	Improved security factor.
l_{Wall}	Length of border wall.
$n_{\text{Arr.}}$	Number of illegal immigrants arrested along the border.
$n_{\text{Att.}}$	Number of attacks on border patrol.
n_{Children}	Number of unaccompanied children that cross the border.
n_{Court}	Number of illegal immigrant court cases throughout the country per year.
$n_{\text{Crim.}}$	Number of criminals that are illegal immigrants.
n_{Deaths}	Number of illegal immigrants who die attempting to cross the border.
n_{Enter}	Total number of illegal immigrants who enter the country.
$n_{\text{Enter Border}}$	Number of illegal immigrants who enter through the border.
$n_{\text{Fam.}}$	Number of illegal immigrant families separated.
$n_{\text{Off.}}$	Number of border patrol officers.
$n_{\text{Off. New}}$	Number of border patrol officer new hires.
n_{Repair}	Number of border wall repairs.
n_{Work}	Illegal immigrant workers in the country.
p_{Border}	Percentage of illegal immigrants who enter through the border.
r_{Crime}	Crime rate in counties along the border wall.
$r_{\text{Crime Ill.}}$	Crime rate, from illegal immigrants, in counties along the border wall.
t_{Court}	Time for a illegal immigration court case from beginning to end.

CHAPTER 1. INTRODUCTION

Whether designed to do so or not, engineered products impact people's lives everyday. How a product changes a person's life is known as the social impact. Some social impacts have been integrated into product design more frequently than others. The impact a product has on a user's health and safety are commonly understood in engineering design, as can be seen by the ubiquitous use of safety factors. The impact a product has on gender roles, family dynamics, and civil rights have been more difficult for engineers to measure, understand, and use as performance measures in product development processes. The purpose of this research is to create tools that engineers can use to understand and improve a product's social impact.

The social impact of a product has been difficult to present in a way that is meaningful to engineers. Engineers are trained to focus on a product's measureable parameters, such as weight, length, and strength, to determine a product's performance. In contrast, when measuring social impacts, data is often qualitative and subjective. Even so Sustainable Development Goals from the United Nations and Grand Challenges for Engineering from the National Academy of Engineering have both identified the need for engineers to help solve the world's social issues [1, 2]. In order for engineers to help solve these problems, methods that can help engineers improve a product's social impact and design product's for specific social impacts are needed.

Typically, engineers are unfamiliar with how to assess and predict the social impacts of a product or program [3]. Though emerging engineering topics, such as energy justice, are beginning to acknowledge the relationship that products have with important social issues, engineers still tend to focus on product capabilities to identify a product's success or failure [4]. A product's impact and success cannot be determined by its functional capabilities alone (many products with promising functionality have been abandoned by consumers) [3]. In the case of improved biomass cookstoves, while the stoves may have improved efficiency, those that do not take the consumer's behavior and environment into account often are not adopted by the consumer [5]. Similarly, a product's success cannot be evaluated based on social impact alone. Other impact areas, such as financial and environmental, should also be considered when developing a product [6–8]. Managing the tradeoffs between these impact areas adds to the complexity of the engineer's job.

One way of measuring a product's impact is by using social impact indicators and social impact categories. Social impact indicators and categories can be used to describe a product's social impact. Social impact indicators are used to know the amount of social impact a product has. Sandhu-Rojon defines indicators as "what we observe in order to verify whether – or to what extent – it is true that progress is being made" [9]. One or more social impact indicators can be chosen to demonstrate the social impact that a product has on a person or group. Social impact indicators can be grouped into social impact categories. In a collaborative work between sociologists and engineers, eleven social impact categories for products were identified [10]. The social impact categories for products they identified are: health and safety, paid work, stratification, civil rights, education, family, gender, population change, conflict and crime, networks and communication, and cultural identity and heritage [10]. We recognize that these social impact categories may seem far removed from an engineer's decisions. Nevertheless, this research will show how a product's features can be connected with one or more of these social impact categories, using social impact indicators. Even though social impact indicators and categories can be used to measure a product's social impact, there currently is no method that engineers can use to identify a product's social impact indicators and categories.

The purpose of this research is to create new tools that engineers can use to measure and predict the social impact of their product's. Chapter 2 of this thesis is the published paper, "Towards a Universal Social Impact Metric for Engineered Products that Alleviate Poverty". This paper introduces a metric named the Product Impact Metric (PIM). It measures a product's social impact in five dimensions and combines the impact into a single score. The PIM can be used to compare the impact of different product because it is measured the same way for all products. Chapter 3 of this thesis is the paper "A Method of Creating First Order Social Impact Models for Engineering". This paper introduces a method of selecting impact categories and indicators in order to create predictive social impact models of engineered products.

CHAPTER 2. TOWARDS A UNIVERSAL SOCIAL IMPACT METRIC FOR ENGINEERED PRODUCTS THAT ALLEVIATE POVERTY

2.1 INTRODUCTION

In 2014, nations around the world collectively provided $161 billion in development aid for developing countries [11]. This includes the projects and programs that engineers are involved in, and has increased progressively throughout history. It is believed that this work changes the lives of people around the world, but measuring its impact has been difficult – yet needed to improve the engineer's ability to positively affect society [12].

Aside from the use of engineering safety factors, traditional product evaluation tools are not designed to measure the social impact of engineered products. Initial metrics for social impact created by industry use both qualitative and subjective quantitative data [13]. As engineers, we tend to prefer data that is quantitative and usable within established laws and equations. Currently, there is no standard metric that measures the social impact of engineered products in this manner. The purpose of this paper is to introduce a metric for engineers to assess and quantify the social impacts of their products.

The metric presented in this paper is called the Product Impact Metric (*PIM*). It quantifies an engineered product's impact on impoverished individuals. It organizes multiple dimensions of impact, and compiles them into one score that can be compared for a variety of products or design alternatives. The dimensions of measurement are health, education, standard of living, employment quality, and security. By measuring all of these dimensions of impact, the *PIM* reveals anticipated impacts and unanticipated impacts. The *PIM* is meant to measure the social impact on people who are deprived of these essential necessities. It is important to recognize that the social impact measured by the *PIM* is a function of the product *and* the consumer [14]. Thus, a social impact of the same product can vary for people in different life situations. For example, a device that gives people clean water will have a greater impact on people who do not have clean water than for people who already do.

Products produced by social entrepreneurs would benefit from a social impact metric. These products are often evaluated by how they affect their consumers and other people involved in their business [15]. Although having a sustainable revenue is still an important factor, the primary basis for decision making in a social entrepreneurial setting is driven by improving underdeveloped social conditions. Product categories that a social entrepreneur might target are water, sanitation, energy, transportation, health, education, and safety, among others. The types of assessment tools for these product categories are often more subjective and less valued by people trained in engineering.

The field of sustainability has brought to light the importance of measuring social impacts. Of the three pillars of sustainability – economic, environmental, and social – social sustainability has received the least attention from industry, possibly because it is the least developed [16]. The results of this can be seen in housing development. Abandoned towns in China, Mongolia, and Egypt were developed without focusing on the essential social infrastructure and conform to an unsustainable model of requiring residents to change their social, historical, and cultural conditions [17]. While the necessity of creating products that are socially sustainable is evident, there is no consensus on a cohesive method of determining if a product is socially sustainable or not [16–18]. Indicators of social sustainability can be classified as lower-order, basic human needs, or higher-order, self-actualization, but in all cases, they still need to be selected for measurement [16]. Ultimately, the metric chosen to characterize social sustainability influences how well a designer can determine their product's social sustainability.

The need for a social impact metric is essential, yet not trivial because of its complexity. Creating a metric is nontrivial because products have both anticipated and unanticipated impacts. For example, when people gain access to clean drinking water not only do they gain access to one of life's greatest necessities but simultaneously see a decrease in the prevalence of disease [19]. Likewise, when people gain access to clean cooking and heating fuels they are able to spend less time collecting firewood while also decreasing their risk respiratory illnesses [20,21]. Additionally, the more education a woman receives, the better off her children will be [22, 23]. Contrarily, negative impacts (such as decreasing crop yields) can result when products disregard religious and community rituals [24]. These unanticipated impacts may not be known and can be missed if the correct indicators are not considered.

Another source of difficulty comes from cultural differences between the engineer and consumers. When the engineer has a different culture, understanding the consumer's point-of-view can be difficult. Culture influences people's perception of a product's value. For example, someone might buy a product simply because it is a "cool, American invention" [25]. This can skew impact results that are based on the number of users and revenue from a product. Metrics that track impacts on a personal level are less prone to cultural bias than metrics considering just the number of people influenced or products sold.

Engineers are typically untrained and unfamiliar with assessing the social impacts of a product or program [3]. Although emerging engineering topics, such as energy justice, are beginning to acknowledge the relationship that products have with social issues, engineers still tend to focus on product capabilities to estimate a product's success or failure [4]. A product's impact and success cannot be determined by its functional capabilities alone (many products with excellent functionality have been abandoned by consumers) [3]. In the case of improved cookstoves, they may have improved efficiency, but stoves that neglect the consumer's behavior and environment are often not adopted by the consumer [5]. Similarly, success cannot be evaluated based on social impact alone. Other impact areas, such as financial and environmental, should also be considered when developing a product [6–8]. Managing the tradeoffs between these impact areas adds to the complexity.

The United Nations Environmental Programme details the methodology they use to create social impact metrics [26]. However, the methodology presented in the report requires the designer to customize the metric for each product. A designer must identify the stakeholders and impact categories before measuring a product's impact [26]. To simplify measuring a product's social impact, when using the *PIM* to evaluate a products social impact, a product designer uses the same metric to measure any product from the perspective of any impoverished stakeholder. This is possible because the *PIM* is measured on the individual level and is built on the framework of the UN's Multidimensional Poverty Index (UNMPI), a single metric that applies to all developing countries.

In order to enhance the abilities of engineers, we suggest that new metrics for measuring product social impacts are needed. These metrics may be specific to a single product, or abstract in order to measure various types of products simultaneously. The measure introduced in this paper (*PIM*), is meant to be a universal metric so that it can be used for all products. By taking a general and not specific approach, the accuracy of the *PIM* is knowingly decreased (it is less likely to show the full depth of a product's impact). Nevertheless, we make this choice for two specific reasons: so that products can be compared and because it mimics the form of the highly usable UNMPI that has been easily understood and applied for years.

In presenting the *PIM*, the remainder of the paper is organized as follows, Section 2.2 explains the origin of the *PIM*, Section 2.3 introduces the *PIM* equations, Section 2.4 introduces important considerations when using the *PIM*, Section 2.5 using the *PIM* for determining the impact of motorcycles in a small Brazilian town, and Section 2.6 is the conclusion.

2.2 The UN's Multidimensional Poverty Index

The *PIM* is inspired by the UNMPI. The UNMPI was created by the United Nations Development Programme (UNDP) and was first part of the Human Development Report in 2010 [27]. The UNMPI measures a population's level of poverty. This is done by analyzing survey data in three specific dimensions: health, education, and standard of living. The UNDP chose these dimensions because they are widely accepted as measures of poverty, but also because these are the only dimensions that had sufficient data for the underdeveloped countries that the UNMPI measures.

The *PIM* shares these three dimensions with the UNMPI and adds two more: security and employment quality. These two additional dimensions were among those that the UNMPI creators wanted to include in the UNMPI but inadequate data at the national level prevented them [28–30]. Other dimensions similarly omitted from the UNMPI were not included in this study because of their reliance on highly qualitative data. They are agency and empowerment, psychological and subjective wellbeing, and ability to go about without shame [31–33].

Some *PIM* calculation methods are changed from the UNMPI. A majority of the changes made are associated with making the *PIM* more sensitive to incremental changes in the data. The dimensions in the UNMPI are binary, in that they are either satisfied or not. The dimensions of the *PIM* are normalized between zero and one, zero meaning they are completely deprived and one meaning they not impoverished. In this way, when a product causes indicator values to have an incremental change, the *PIM* score will be able to measure it.

We acknowledge that there is risk in adapting the UNMPI metric, which was designed to characterize national-level poverty and using it to characterize individual-level poverty as we have done in this paper. There is also risk in adding dimensions to the poverty characterization as we have also done in this paper. Nevertheless we believe the risk to be minimal for the following reasons: (i) The dimensions of the UNMPI are collected by the UN at an individual level, and later aggregated to characterize national-level poverty. (ii) The dimensions that we have included are additions to the UNMPI recommended by the UN, but not implemented due to insufficient data across all nations, which disables it for the UN's purpose of nation-by-nation comparison.

The UNMPI was an essential building block for creating the *PIM*. We started with it because it is globally recognized, debated, and refined. We have confidence that this makes the *PIM* a metric that can be used by people familiar and unfamiliar with social impact because interpreting UNMPI scores does not require training or significant explanation. By learning from the UNMPI and other insight gained from literature and our experience, we believe the *PIM* captures a necessary multidisciplinary perspective.

2.3 Proposed Metric

The equations that make up the *PIM* follow here accompanied with clarification of the calculation methods. The calculations are organized by measurement dimension as well as the consumer's characteristics.

2.3.1 Mathematical Relationships

The equation for the Product Impact Metric,

$$PIM = M_i - M_{i-1} \tag{2.1}$$

includes the multidimensional poverty level before (M_{i-1}) and after (M_i) the introduction of the product. In this way, the *PIM* measures how the product affects the consumer by determining the difference in a consumer's level of poverty. It can be either positive or negative, reflecting a product's positive or negative impact on the consumer.

It is important to recognize that Eq. 2.1 comprises two distinct but related metrics: M and PIM. M is a measure of an individual's poverty level, while PIM measures the change in an individual's poverty level over a certain amount of time.

The multidimensional poverty level,

$$M = \frac{1}{5}(H + E + L + Q + Y) \tag{2.2}$$

includes the following measurement dimensions: health (H), education (E), standard of living (L), employment quality (Q), and security (Y). All of the dimensions (H, E, L, Q, Y) are scaled to be between zero and one, thus making them equally weighted. To preserve universal comparison from product to product across many researchers, we strongly discourage weighting these factors differently without explicitly acknowledging it to be a weighted PIM. This measure is meant to be universally useful to all products and by adding weights to certain dimensions, it becomes favorable of certain products and thus less universal.

In developing M, two possible methods of combining these dimensions were explored, using a geometric mean and an arithmetic mean. The arithmetic mean was selected because of certain drawbacks of the geometric mean. When using a geometric mean, if the person is deprived of one dimension, the entire M score is zero, regardless of the other dimensions. An arithmetic mean allows a dimension to equal zero without forcing M to be zero. If a product has some negative impacts but the total PIM score is positive, the negative impacts will be evident when taking the difference of before and after the product introduction for each dimension and can be conscientiously assessed individually. By identifying the dimensions with a negative impact, the product can be changed and improved to increase its positive impact.

In many ways M characterizes the life conditions of those in poverty, which may at times seem disconnected from the product features controlled by the design team. However, some products and their features can change the life conditions of those in poverty. For example, the design of outdoor nighttime lighting can have a direct impact on the security of an individual who would otherwise need to access the area in darkness [34, 35]. The features of the design, such as the lumens produced, quality of light distribution, and battery life directly affect how well the product improves ones security.

As introduced in this paper, the *PIM* characterizes the change in M, and can be attributed to a product when M is assessed before the individual has access to the product (M_{i-1}), and assessed again after the individual has had access to the product for a period of time (M_i). For the *PIM* to be meaningfully attributed to a product, M_{i-1} must be assessed immediately before the individual gains access to the product. Thus, the change in poverty level will be evaluated for the full time the individual was exposed to the product. Furthermore, to be a realistic assessment of a product's impacts, the *PIM* must be adjusted by the *PIM* of a control group that does not have access to the product over the same period of time. This more realistic assessment is represented by Eq. 2.23, and discussed more deeply in Section 2.4.3.

The Product Impact Metric accounts for impacts in these five dimensions of measurement (H, E, L, Q, Y) because they are simple to measure and indicative of a person's level of poverty [28,36]. Each dimension is made up of sub-dimensions, marked with carrots ($[\check{\ }]$), that include the field measurements and standard measurements. Field measurements are collected directly from the consumer, such as their weekly working hours. Standard measurements, such as the national poverty line, can be collected from online databanks or other legitimate sources of national and regional data. Some of the values of the standard measurements can be found in Table 2.1. Each sub-dimension follows the form,

$$[\check{\ }] = \begin{cases} \frac{\text{Num}}{\text{Den}}, & \text{Num} < \text{Den} \\ 1, & \text{Num} \geq \text{Den} \\ 0, & \text{Num} \leq 0, \text{Den} \leq 0 \end{cases} \tag{2.3}$$

in order to normalize its value between zero and one. The calculation of each dimension is completed by finding the average of the sub-dimensions.

Some of the standard measurement values used in calculating the *PIM*, namely acceptable sanitation facilities per family ($n_{tf\alpha}$), water distance maximum ($d_{w\alpha}$), acceptable years of schooling ($n_{l\alpha}$), average good BMI ($s_{\text{BMI}v}$), and malnourished BMI ($s_{\text{BMI}a}$), are taken from what USAID and Centers of Disease Control and Prevention currently use as their standard acceptable values [37,38]. When these values are updated by these organizations, the standard measurements in the *PIM* should also be updated. These standard measurements are the same globally. This is consistent with USAID and CDC practice. There are a few acceptable limits, however, that are treated on a region-by-region basis when calculating the *PIM*. These are the regional poverty line (m_{yo}) and average regional working hours per week ($h_{k\alpha}$).

2.3.2 Measurement Dimensions

As the *PIM* can measure all different types of products, the measurements were chosen in a way to assist in data collection. Five guiding principles were established on how the data for the *PIM* could be collected easily, affordably, and quickly. First the field measurements must be simple enough that they can be collected in a survey in one sitting, not needing observations throughout a day. Second, measurements should not measure impacts that are directly related to only one product type, such as water contamination levels. Third, the consumer should be able to answer the survey without having to reference other materials, referencing an energy bill to determine kW · hr used in a month. Fourth, the measurements should include minimal subjective opinion and judgment from the engineer and consumer. Lastly, all measurements must be scalable from a person who is completely deprived to a person having an acceptable level.

Health

The equation for health is,

$$H = \begin{cases} \frac{1}{2}(\check{N} + \check{B}), & \text{Has children dependents} \\ \check{N}, & \text{Has no children dependents} \end{cases} \tag{2.4}$$

where $\check{N}$ is the subdimension for nutrition and $\check{B}$ is the subdimension for child mortality. Their equations are

$$\check{N} = \frac{s_{\text{BMI}v} - |s_{\text{BMI}v} - s_{\text{BMI}r}| - s_{\text{BMI}a}}{s_{\text{BMI}v} - s_{\text{BMI}a}} \tag{2.5}$$

where the

$$\check{B} = \frac{n_c - n_{cb}}{n_c} \tag{2.6}$$

and the equation for the number of children (n_c) is,

$$n_c = n_{cz} + n_{cb} \tag{2.7}$$

Health includes measurements for the average healthy body mass index (BMI) score ($s_{\text{BMI}v}$), the measured BMI ($s_{\text{BMI}r}$), malnourished BMI score ($s_{\text{BMI}a}$), number of children (n_c), number of child deaths (n_{cb}), and the number of living children (n_{cz}), see Tables 2.1 and 2.2 for standard field measurements. A BMI score includes measurements of height, in meters, and mass, in kilograms. The equation for calculating BMI is, $s_{\text{BMI}} = \text{weight}/\text{height}^2$. In $\check{N}$, the BMI scale is the same for all adults but changes throughout a child's life. Children have lower BMI scores than adults and so their healthy and malnourished BMI scores are also lower. The values of ($s_{\text{BMI}v}$) and ($s_{\text{BMI}a}$) can be found in growth charts produced by the Centers for Disease Control and Prevention [38]. The healthy BMI score, ($s_{\text{BMI}v}$), is the 50th percentile and the malnourished BMI score, ($s_{\text{BMI}a}$), is the 5th percentile.

Table 2.1: Standard measurements used in the calculation of the *PIM*.

Standard Measurements	**Values**
Health (H)	
Average good BMI ($s_{\text{BMI}v}$)	21.75*
Malnourished BMI ($s_{\text{BMI}a}$)	16*
Education (E)	
Acceptable years of schooling ($n_{l\alpha}$)	8*
Standard of Living (L)	
Water distance maximum ($d_{w\alpha}$)	200 m
Acceptable sanitation facilities per family ($n_{tf\alpha}$)	1
Hours maximum of electricity ($h_{e\alpha}$)	168 hrs
Monthly income poverty line (m_{yo})	Regional
Employment Quality (Q)	
Average regional working hours ($h_{k\alpha}$)	Regional
Security (Y)	
Total number of protection parameters ($n_{p\alpha}$)	5
Total number of exposure parameters ($n_{x\alpha}$)	5

* For adults

Table 2.2: Field measurements used in the calculation of the PIM.

Field Measurements
Health (H)
Height
Mass
Measured BMI ($s_{\text{BMI}r}$)
Total number of children (n_c)
Number of living children (n_{cz})
Child deaths (n_{cb})
Education (E)
Children in school (n_{cl})
School aged children (n_{clg})
Individual's years of schooling (n_{ql})
Standard of Living (L)
Clean Fuels ($n_{y\alpha}$)
Dirty Fuels ($n_{y\beta}$)
Sanitation facilities per family (n_{tf})
Water distance (d_w)
Hours with access to electricity (h_e)
Monthly income (m_y)
Employment Quality (Q)
Weekly working hours (h_k)
Weekly work hours lost due to injury (h_{kj})
Security (Y)
Number of protection parameters (n_p)
Number of exposure parameters (n_x)

Calculated Measurements
Measured BMI ($s_{\text{BMI}r}$)
Multidimensional Poverty Level (M)
Product Impact Metric (PIM)

Education

The the equation for education is,

$$E = \begin{cases} \frac{1}{2}(\check{S}_c + \check{S}_q), & \text{Has children} \\ \check{S}_q, & \text{Has no children} \end{cases} \tag{2.8}$$

where $\check{S}_c$ is the sub-dimension for child schooling and $\check{S}_q$ is the sub-dimension for the individual's level of schooling. Their equations are

$$\check{S}_c = \frac{n_{cl}}{n_{clg}} \tag{2.9}$$

$$\check{S}_q = \frac{n_{ql}}{n_{l\alpha}} \tag{2.10}$$

Education measurements are the number of children in school (n_{cl}), the number of school aged children (n_{clg}), the years of schooling of the individual (n_{ql}), and the acceptable years of schooling ($n_{l\alpha}$). Tables 2.1 and 2.2 specify which are standard or field measurements.

Standard of Living

The equation for standard of living is,

$$L = \frac{1}{5}(\check{F} + \check{T} + \check{W} + \check{E} + \check{I}) \tag{2.11}$$

where $\check{F}$ is the sub-dimensions for household cooking and heating fuels used, $\check{T}$ is the sub-dimension for sanitation access, $\check{W}$ is the sub-dimension for clean water access, $\check{E}$ is the sub-dimension for electricity usage, and $\check{I}$ is the sub-dimension for income. Their equations are

$$\check{F} = \frac{n_{y\alpha}}{n_{y\alpha} + n_{y\beta}} \tag{2.12}$$

$$\check{T} = \frac{n_{tf}}{n_{tf\alpha}} \tag{2.13}$$

$$\check{W} = \frac{d_{w\alpha} - d_w}{d_{w\alpha}} \tag{2.14}$$

$$\check{E} = \frac{h_e}{h_{e\alpha}} \tag{2.15}$$

$$\check{I} = \frac{log\ m_y}{log\ m_{yo}} \tag{2.16}$$

Standard of living measurements are the number of clean fuels used in the home ($n_{y\alpha}$), the number of dirty fuels used in the home ($n_{y\beta}$), the number of sanitation facilities per family (n_{tf}), acceptable number of sanitation facilities per family ($n_{tf\alpha}$), maximum acceptable distance to an improved water source ($d_{w\alpha}$), the distance to an improved water source in meters (d_w), the number of hours of electricity per week (h_e), maximum hours of electricity per week ($h_{e\alpha}$), monthly income per capita of the family (m_y), and the national poverty line (m_{yo}). See Table 2.1 for details about the standard measurements and Table 2.2 for the field measurements.

In $\check{F}$, dirty fuels are those that produce large amounts of smoke, like biomass, coal, and others. Clean fuels are those that do not have high emissions such as propane. Burning dirty fuels in improved cookstoves that lower household emissions within a similar range to clean fuels, are counted clean fuel. Electricity is also considered a clean fuel because there are no household emissions.

For $\check{T}$, an acceptable sanitation facility is one that can be visited in private, is free of feces, and has few flies. This follows the standards set out by the United States Agency for International Development (USAID) and other organizations [37]. USAID guidelines state that facilities that are in the open and bucket latrines do not count as sanitation facilities. If bucket or container latrines are maintained by a sanitation service, it is considered a suitable sanitation facility for the PIM.

Approved water sources, in $\check{W}$, also follow guidelines set by USAID [37]. If a water source is a maintained source of clean water, like a well, piped water, or a public fountain, then it should be counted as a water source. Unimproved water sources include rivers, streams, and lakes and are not counted. If an improved water source is know to be contaminated, it is not counted as a water source.

Hours of electricity, h_e in $\check{E}$, is the hours of plug-in electricity that the home receives. This can include power from a battery or generator if it is a reliable source and can produce power sufficient for more than just lighting.

The monthly income, m_y in $\check{I}$, is the per capita income of the family. The incomes of all members of the family are included. The national poverty line should be taken from a reliable source such as a government or employment website and should be on a monthly scale. The log function is used in the income sub-dimension equation so that as an individual who has less money is more impacted by an increase in income than someone who already has a higher income. The same log function is used in the UN Human Development Index to scale the impact of increasing income.

Employment Quality

As employment quality is not included in the UNMPI, a new equation for employment quality was created, and is,

$$Q = \frac{1}{2}(\check{R} + \check{J}) \tag{2.17}$$

where $\check{R}$ is the sub-dimension for hours of employment and $\check{J}$ is the sub-dimension for work related injuries. Their equations are

$$\check{R} = \begin{cases} \frac{h_k}{h_{k\alpha}}, & \text{Independent or Dependent, Able} \\ \frac{h_{k\alpha}-h_k}{h_{k\alpha}}, & \text{Dependent, Not able, Working} \\ \frac{h_{k\iota}}{h_{k\alpha}}, & \text{Dependent, Not able, Not Working} \end{cases} \tag{2.18}$$

$$\check{J} = \begin{cases} \frac{h_k-h_{kj}}{h_k}, & \text{Independent or Dependent, Able} \\ \frac{h_k-h_{kj}}{h_k}, & \text{Dependent, Not Able, Working} \\ \frac{h_{k\iota}-h_{kj\iota}}{h_{ki\iota}}, & \text{Dependent, Not Able, Not Working} \end{cases} \tag{2.19}$$

Employment quality includes measurements for the weekly income-generating hours (h_k), regional acceptable income-generating hours per week ($h_{k\alpha}$), weekly hours of lost employment due to work injury (h_{kj}). Measurements with a subscript iota (ι), indicate that the measurement is taken from the independent provider and not the consumer being surveyed. See Tables 2.1 and 2.2 for the standard a field measurements Weekly working hours, should represent a normal work week schedule and not account for holidays or injury time off. The independent provider's numbers are used to reflect the situation of the consumer when they are completely dependent on their provider. In equations 2.18 and 2.19, someone who is able, is physically and mentally able to work. This does not include children or the elderly. Also, dependents are people who rely on another person to provide for them financially.

Security

Similar to employment quality, the equation for security was created as part of this paper. The equation for security, is,

$$Y = \frac{1}{2}(\check{P} + \check{O}) \tag{2.20}$$

where $\check{P}$ is the sub-dimension for protection and $\check{O}$ is the sub-dimension for exposure. Their equations are

$$\check{P} = \frac{n_p}{n_{p\alpha}} \tag{2.21}$$

$$\check{O} = \frac{n_{x\alpha} - n_x}{n_{x\alpha}} \tag{2.22}$$

Security includes measurements for the number of protection parameters (n_p), maximum number of protection parameters ($n_{p\alpha}$), the number of exposure parameters (n_x), and the maximum number of exposure parameters ($n_{o\alpha}$). Literature on crime was examined and five factors of both protection against and exposure to crime were extracted [39–43]. The protection parameters are the presence of a local police force, ability to lock the entire house, organized after school activities for children in the neighborhood, no criminal past, and that the consumer lives with trusted people. The exposure parameters consider if a person is a drug or alcohol user, a business owner, must leave the house at night, if there is criminal activity in the neighborhood, and if the neighborhood is resource poor.

To increase the metric's consistency, clarification of these parameters is necessary. The protection parameter "ability to lock the entire house" can only be satisfied if every door and window can be shut and locked or if a secure wall or fence circles the home and can be locked. Organized after school activities for children must be organized by a school or other community organization and be supervised by adults. Simply having places where children can participate in activities, such as parks, does not qualify. In order for someone to be a trusted roommate, the consumer has to have known them for at least one year. Living alone is counted as not living with a trusted roommate. In order to have the exposure parameter for leaving the home at night, the purpose of leaving the home must be a necessity and not for pleasure or leisure. Such necessities include, but are not limited to, traveling to and from work, getting to a sanitation facility, and fetching water, firewood, or other resources. Also, the trips out of the house must occur on a weekly basis in order to qualify. Finally, resource poor neighborhoods are those where a majority portion of the community do not have sufficient food, water, energy, or other resources. This does not have to include the consumer who might have sufficient resources but refers to the conditions of the community. These guidelines are meant to clarify the measurements that will need to be taken and assist those who use the *PIM*.

2.4 Using the PIM

It is worth pausing to consider how the *PIM* could be used by designers. The purpose of the *PIM* is to assist in designing for social impact, as it can guide the designer to consider the basic dimensions of poverty (health, education, standard of living, employment quality, and security), and the conditions that affect them.

Designers can use the *PIM* in various ways; they can use the *PIM* to predict how specific design concepts and features would contribute to an individual's level of poverty, thus allowing designers to quantitatively determine how impactful a product is. Designers can also use the *PIM* to assess and benchmark the impact of existing products, which can valuably inform the creation of new products.

The *PIM* helps designers predict and assess positive and negative impacts of a product, which is particularly meaningful as designers seek to mitigate newly identified negative impacts before launching a product onto the market. The *PIM* is particularly useful in identifying anticipated and unanticipated impacts so that during the design process impacts can be accounted for across multiple dimensions. The multidimensionality of the *PIM* supports the notion that poverty is related to more than just income [44, 45].

2.4.1 Measuring Impact on an Individual Level

Under some conditions, the *PIM* score for a given product is different depending on the individual being impacted. While for other conditions, a single *PIM* calculation can characterize a product's impact for multiple similar individuals. This is simply because a product's impact is a measure of how well a product's functionality (or other features) satisfies the needs of an individual. Given that individuals have different needs, the product's impact varies person-to-person when those people experience different levels of poverty.

In a real way, the *PIM* provides the designer with insights similar to those gained by stress analysis in mechanical design. The resulting stress is a function of both the applied load and the conditions of the structure (e.g., restraints and geometry). Stress analysis in mechanical design is specific to the structure and loads being considered. In other words, the same load applied to two disparate structures results in two different stresses. Similarly, as indicated by the *PIM*, a poverty-alleviating product given to an individual – at one level of poverty – will have a different impact on that individual than on someone else at a different level of poverty.

Likewise, the same load applied to multiple similar structures will result in similar mechanical stresses across all such structures. Thus, the *PIM* can be used to predict or assess how impactful a product would be at helping people with similar needs and those in similar demographics. To make the best use of the *PIM*, the designer must exercise judgment about how broadly to represent the demographic in the analysis.

2.4.2 Measuring Anticipated and Unanticipated Impacts

While the *PIM* can be applied to all types of products, some engineers may be discouraged using it because their product's anticipated impacts may not be directly measured by the *PIM*. While this is a valid concern, the *PIM* will capture secondary, often unanticipated, impacts. The *PIM* does not differentiate between these; it measures any impact within its scope.

To illustrate this, an example case has been created using a persona that receives access to water from the Village Drill, a human-powered borehole drill [46]. The use of personas is further explained in Section 2.4.4. The persona, Adia, is a farmer in Kenya who otherwise has relied on rainwater and fetching water to irrigate her crops, see Fig. **??**. The anticipated impact of the Village Drill is a decreased distance to water. The unanticipated impacts of the Village Drill are an increase in the number of her children attending school, an increase in her income, a decrease in her injury hours, and improvements to her security. In her case, the anticipated impact, the distance to water, has a *PIM* score of only 0.04. The unanticipated impacts account for the rest of the total *PIM* score, which is 0.1530 before and 0.1502 after subtracting the counterfactual. If the only measurements taken on the Village Drill pertained to the water that was given, most of the impact that makes up the *PIM* score would not be measured.

ADIA

FARMER

Adia lives with her husband and 4 children in a small village in Western Kenya. She owns a small piece of land where they farm vegetables and grain every year. They rely on rain water as their main source of water for their crops. Any surplus crops they have, they sell. When there is no rain, they get water from a stream 2 km away and hand water their crops. Their drinking water comes from the stream as well. She and her family make trips to the stream to fetch water in jugs and buckets. The water from the stream is dirty, and they don't have access to other water sources. Her children don't go to school consistently because she needs their help at home and on the farm. The children are also often sick from the bad water.

Goals: Increase crop yield, send children to school, spent time at home making items that she can sell

Pain Points: Carrying water has made her have back pain, children don't go to school

Indicator	**Before the Bore Hole**	**After the Bore Hole**
BMI	16	18
Total Children	4	5
Child Deaths	1	1
School Aged Children	3	3
Children in School	2	3
Individual's Years of School	3	3
Clean Fuels	0	0
Sanitation Facilities per Family	0	0
Distance to Clean Water (m)	2000	20
Electricity Use (hours)	0	0
Income (Kenyan Shillings)	1200	1600
Poverty Line (Kenyan Shillings)	1562	1562
Weekly Hours Toward Income	48	48
Work Hours Lost to Injury	8	2
Protection	2 (No criminal past, lives with trusted people)	3 (No criminal past, lives with trusted people, house locks)
Exposure	2 (Business owner, leave home at night)	1 (Business owner)
Multidimensional Poverty Level (M)	**0.5336**	**0.6866**
Product Impact Measure (PIM_ϕ)		**0.1530**
PIM for counterfactual (PIM_τ)		**0.0028**
PIM actual (PIM_δ)		**0.1502**

Figure 2.1: Adia buys a bore hole from a team of drillers using the Village Drill and its impact on her is shown here.

2.4.3 Including a Counterfactual

In order to attribute an impact to a single product, the impacts of other products, projects, and social influences acting on the consumer can not be ignored. The sum of these external influences, which also contribute to the social progression of consumers, is called the counterfactual [47]. A common approach for determining the counterfactual is taking measurements from a control group concurrently with the measurements of the impacted group. If the *PIM* results are not compared to a counterfactual, then all the social improvement the consumer has are attributed to the product, which may or may not be true. Especially in developing countries, there are other factors and groups that are trying to improve peoples lives, such as government programs. Thus, alongside the measurements that are taken for the group of impacted consumers (PIM_ϕ), measurements must be taken of a control group (PIM_τ). Using a method called difference-in-differences, the *PIM* of the control group is subtracted from the impacted group

$$PIM_\delta = PIM_\phi - PIM_\tau \tag{2.23}$$

to determine the true impact (PIM_δ) [48]. The *PIM* score should not be reported unless it is the score for PIM_δ. This is the score that can be attributed to the product. Measuring both a control group and an impacted group can be expensive and difficult to manage for many engineering groups. A method to reduce the cost of these measurements is by using personas.

2.4.4 Using Personas

Field survey data collection is very expensive and out of the scope of many engineering projects. When the engineer is far from the consumer, travel costs are high and time with consumers is limited. In order to reduce the costs and complexity of impact assessment, personas based on actual data may be used to simulate people who would use the product. Personas are a design tool used in human centered design [49]. They are a representation of a possible consumer and used to focus product design efforts. In the *PIM*, they are used to predict possible impacts on the consumer and create a counterfactual. Databanks such as World Bank, have data similar to the *PIM* measurements, though they are on a national level. Measurement values can be generated from this data to create a persona that can be used to assess the impact of a product on a consumer. Additionally, control personas can be produced for the counterfactual. Using databank data collected over a similar time period as the data collected for the *PIM*, PIM_τ can be created so that a more accurate impact can be found.

Personas should be analogous to the projected consumer group. Only when personas closely match the consumers will their *PIM* score be accurate. Also, more research than retrieving indicators is necessary. The type of work, family structure, environment, and other social factors should be known while creating an acceptable persona. This research also prepares the engineer to know how the product will affect the consumer. An example of a persona and product assessment is in Section 2.4.2. Additionally, it is beneficial to observe the impact on men, women, and children. Deprivation among women and children is known to be higher than men, especially in low income countries [23, 50]. Also, women and children are more impacted by products meant to reduce poverty [51]. Both of these factors offer evidence that the *PIM* score has potential to be higher for women and children than for men. This information should be factored into the decision of who the persona is.

2.4.5 Time

Long term analyses of products in the developing world are not common practice, though they should be. Unfortunately, it is more common to publish results of a product or project soon after launch. Long term analyses give more information on how the product is accepted and if it is useful to the consumers. In order to motivate more long term product assessments, the *PIM* includes indication of the time attributed with the data collected. A subscript of the number of months of use the product has is included with the *PIM* score. If a product has a PIM_{δ} score of 0.56 after 20 months of use, then the score should be displayed as 0.56_{20}. *PIM* scores that have more time, demonstrate sustained impact and are vital to learning more about product social impacts. Using this time element makes the *PIM* more transparent and scores that have more time should be recognized as being from a more substantial data set.

2.5 Validation Study

The following study was done by the authors to demonstrate how the *PIM* can be used, what can be learned from using the *PIM*, and how personas can be used in *PIM* calculations.

Sociologists use ex ante (predictive) metrics and ex post (assessment) metrics. The *PIM* is an ex post metric that can also be used as an ex ante metric. It is common practice to compare ex ante values to ex post measurements, which is what will be done in this study [47].

The study presented in this paper was conducted in Amazonas, Brazil. The product used in the study is the motorcycle because of it's prevalence in the area and its studied impact.

2.5.1 Subject and Location Background

The study was conducted in Itacoatiara, Amazonas, Brazil. Itacoatiara has an estimited 99,854 citizens and is on the Amazon River, 169 miles from the state capital, Manaus [52]. It is surrounded by the dense and impassible Amazon rainforest. The only way in and out of the city for motorcycles is the AM-010 highway which ends in Itacoatiara. However, very few people choose to ride their motorcycles on the highway between Itacoatiara and Manaus. This condition causes Itacoatiara to be a closed system of motorcycles.

In Itacoatiara, unlike the rest of Amazonas and Brazil, a large percentage of the transportation in and around the city is done by motorcycle. In 2016 the city of Itacoatiara had 2,947 cars, 10,041 motorcycles, and 7,108 mopeds registered [52]. Of the 355 people that we interviewed 59% of them own a motorcycle, 16% own a car, 30% own a bicycle, and 22% own none of these products. Some of the common jobs involving motorcycles are: motorcycle taxi driver, delivery by motorcycle, motorcycle washing, motorcycle mechanic, and motorcycle tire sales. Motorcycle taxi driver is an especially popular occupation in Itacoatiara. In Itacoatiara it is estimated that there are up to 3,000 motorcycle taxi drivers. People use motorcycle taxis for many reasons, going to the gym, going to work, visiting family members, going to the town center for business, and taking children to school. While 209 of the 355 people we surveyed own motorcycles, 219 people said that motorcycles were their main form of travel. Some people who don't own a motorcycle use the motorcycle taxi drivers as their main form of transportation in town.

Some of the impacts of motorcycles on people are known. Motorcycles have had a measurable impact on people's access to employment, education, and fertility [53]. Motorcycle usage also has negative effects on people's health due to pollution and accidental harm. Older motorcycles in Brazil emit more pollutants than cars per passenger-km [54]. Additionally, from the year 2000 to 2006 for every 1000 motorcycles sold in Brazil there were 1.24 recorded fatalities and 3 recorded hospitalizations from motorcycle accidents [54].

2.5.2 Data

For the study, we conducted 355 surveys of people who live in Itacoatiara. The survey had all of the necessary responses needed to collect a multidimensional poverty level (M). It also asked

Figure 2.2: Itacoatiara and its immediate surroundings.

them if they owned a car, motorcycle, bicycle, boat, and some common household products such as a television and microwave. It asked them which mode of transportation did they use most and how often they used the bus, taxi, and motorcycle taxi. Of the people that completed the survey, 51 were asked additional, open response questions about how they use their mode of transportation, how long they have owned them, their work, and their aspirations.

Additional data in this example comes from The World Bank's databank. Data from this databank was used to create the the M_{i-1} point on both Figure 3.7 and Figure 2.3. The counterfactual for this study is a representation of the unemployed people that we surveyed. The average unemployed person we surveyed can be represented by the 5.5th percentile of the Brazilian population.

At the end of our study, we asked people on social media who live in and around Itacoatiara about how motorcycles have impacted their lives. We received responses from 16 people who told us what mode of transportation they use and how it impacts their life.

2.5.3 Analysis

Throughout the study, it became obvious that one group of people who were significantly impacted by their motorcycles are the motorcycle taxi drivers. They cannot work without them and only have a job because they own one. Also, many of them have been in accidents and lost work hours.

The people we use to calculate the *PIM* are people who would be most benefited by owning a motorcycle, people who are currently unemployed and do not own a motorcycle. If these people obtain a motorcycle it is possible that they would become motorcycle taxi drivers. During our study, we met many people who bought their motorcycle in order to become a motorcycle taxi driver or often fall back on being a motorcycle taxi driver when there isn't other work. Of the 355 people we surveyed, 28 were unemployed and did not own a motorcycle. The survey responses of these people were used to create an M_i score, see Figure 2.3, point M_i UE. The M_{i-1} value for this example comes from data from The World Bank. The percentile of the current unemployed person was projected back to the year 2014. The other M_i value, point M_i MTD, comes from the motorcycle taxi driver data, specifically, the drivers that have owned their motorcycle for three years.

In this example we have made three different predictions about what impact motorcycles have on unemployed people in Itacoatiara. The predictions were done using different information and resulted in different values, see Figure 3.7. The first prediction (P1) was using data from literature on the social impacts of motorcycles in Brazil and in other countries with similar reliance on motorcycle travel [53–55]. The literature does not say how much certain measurements, such as income, change because of motorcycles, instead it listed how social behavior, opportunities, and interactions changed. This prediction had a 89.9% error from the assessed impact.

The second prediction (P2) was made after conducting interviews with motorcycle taxi drivers and determining from their experience and comments what the impacts might be. The additional information provided were the change in measurements of determined impacts as well as new impacts, such as security impact of them working late at night. This prediction had a 25.7% error from the assessed impact.

The last prediction (P3) was made after assessing the measured impact found for a specific group of motorcycle taxi drivers, those who have owned their motorcycle for three years. All of

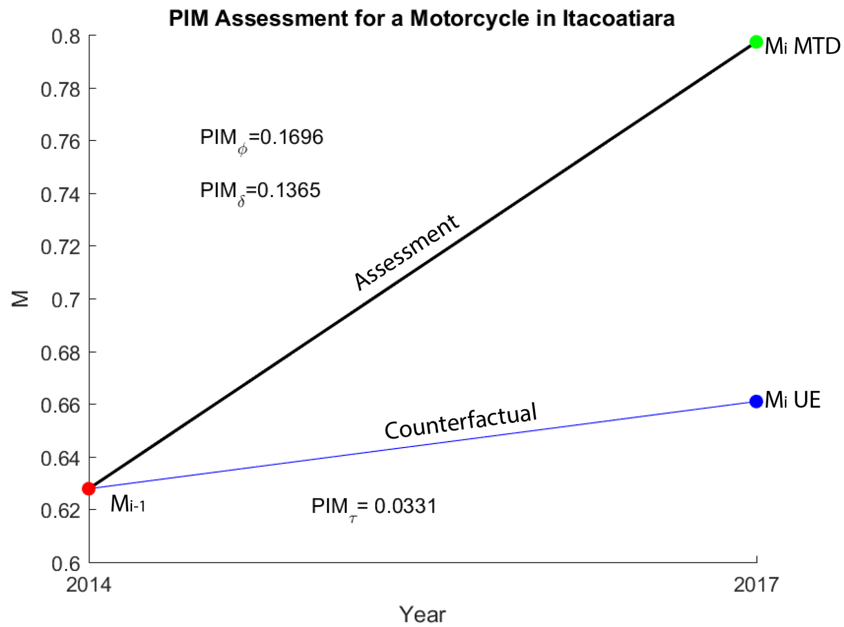

Figure 2.3: Assessment of the PIM score of motorcycles on motorcycle taxi drivers.

the differences in measurements were included in the prediction, which made it much closer to the assessment. The last prediction's PIM_τ is the closest to the PIM assessment and only had 2.3% error from the assessed impact. Clearly, as we gained more information about the product's impact, the error in our predictions decreased.

Counterfactuals were created as described in Section 2.4.3 using data from the World Bank. Personas were created for 5.5th percentile and were tracked for the three most recent years, 2013 and 2016. Wherever there was insufficient data for a year, the data was extrapoled from the two previous years. We made the assumption that the change in these numbers would be the same as the change that would occur between the years 2014 and 2017.

Without context, the M can be difficult to understand. During our study we surveyed someone who was jobless, homeless, and begging for money outside of a grocery store. He didn't have access to water, electricity, sanitation, security, or help from his family. His M score taken from the survey answers that we received is 0.4506. His score was not zero because he did make money begging on the street, he had received his basic education, and was in moderately good health. In order for a person to have a score of zero, they have to be completely deprived in all of the dimensions. In the course of our study, we didn't survey anyone who met this criteria.

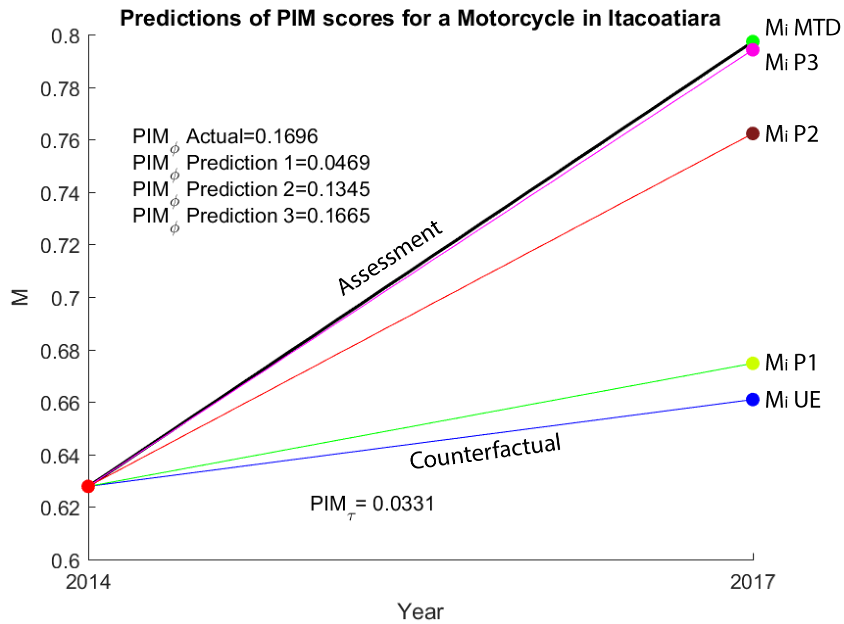

Figure 2.4: PIM score predictions of motorcycles on unemployed people who do not own a motorcycle.

2.5.4 Results of this Study

In this study, we were able to use the *PIM* to assess and predict the impact of a common product. Motorcycles in Itacoatiara have a 0.1365 *PIM* impact on people who are unemployed. Using the data that we collected from motorcycle taxi drivers, we were able to make a prediction that was only in error by 2.3%. Our prediction shows that the motorcycles have a positive impact, but it does have negative impacts. Motorcycles positively impact income and working hours which could have a *PIM* score as high as 0.22, but the motorcycle's negative impacts, the number of injury hours, security exposure of the rider, and an unhealthy increase in BMI, limit its *PIM* score to 0.1365. This knowledge could be used to design motorcycles that have a greater impact on their users.

We were able to use the *PIM* in a real situation and learn more about how such a survey and data collection process can be done. It took less than 5 minutes to obtain all of the information needed from one person to make a single *M* value. When done in a survey form, many people were able to give their information at once by filling out their own survey, this reduced the time per survey dramatically. We were not able to collect data over a long enough period of time to create two M values and calculated the PIM directly from the people we surveyed, but were able to use the additional survey data we collected to create the second M value. Personas were also used to create a counterfactual that was used to account for how the population is changing year after year. The values from this counterfactual were used to calculate the true impact, PIM_δ.

Eventually, a study must be done that looks at the long term impact of a product using the PIM. Such a study would follow the same people over a long period of time so that less assumptions would be made. Such a study could be done on a new product or existing technology. This would remove the largest assumptions that is made in this example. This might also give more information on how a product's impact changes over time.

2.6 Conclusion

Engineers are generally trained to focus on the product's measurable metrics that give precise indication as to whether goals are met. Because of the nature of social and product impact, creating a tool that gives a similar indication of success has proven difficult. Engineers tend to not have the education or training on how to create social impacts [3]. Along with this, selecting indicators to measure social impact is not a skill most engineers have. The approach of the PIM is to stay more general and abstract so that it can be used for all types of products, without modifying the metric.

Determining the anticipated and unanticipated impacts of engineered products on people in poverty is the purpose of the Product Impact Metric. Without measuring for potential unanticipated impacts, the extent of a product's influence on consumers is not entirely captured. Even when products have different impacts, their PIM scores are of the same unit. Therefore, the PIM can be a means of comparing products that impact poverty. This can assist organizations seeking to generate a large social impact because they would be able to choose the products they distribute based on the product's social impact, provided by the PIM.

Also, products that have high impacts and long trial times can teach engineers more about social impact. New insight can be gained from these products about why they might have a greater impact than others. This can be used to create better product design tools for creating products meant to alleviate underdeveloped social conditions.

The Product Impact Metric does have shortcomings. First, it is only valid with consumers who are deprived. A product that is meant to relieve deprivation, will not have a large impact on someone who is not deprived. If measuring from personas or people who are not deprived, a negative *PIM* score can result. A negative score indicates that the product makes someone more depriverd or that the market chosen is not ideal. Although the example given in the paper is of a product in a developing country, the *PIM* can be used for any product that is meant to improve poverty conditions – in any part of the world.

Second, because the *PIM* measures impact on an individual level, measuring the *PIM* from more than one consumer can result in different values. Social impact is a function of the consumer's conditions and the product, so it can change from person to person. This might also be a strength because assessing the impact of the product beyond just one stakeholder can lead to additional findings. A product can have an impact on anyone who interacts with the product.

Third, because the *PIM* is a universal and general metric, it might miss very specific impacts. While it may not collect all potential anticipated impacts, it does measure impacts that are indicative of a consumer's poverty level. The *PIM* was created to make it easy to use. The measurements needed can be collected in a single survey, are broad enough to capture impacts of many types of products, do not require the consumer to provide any information that they might have to find or otherwise do not know immediately when asked, are not dependent on the opinions of the consumer or engineer, and are scalable from a person who is completely deprived to a person who is not impoverished. Future work must be done to create additional, more specific metrics that can give specific impact results while still accounting for unanticipated impacts. Such metrics could also become design tools used by engineers, alongside the *PIM*.

Another limitation of the current study is the static nature of the *PIM*. We simply do not consider how the *PIM* changes overtime in this paper, though we feel that studying the dynamics of the *PIM* could lead to important insights.

In this paper we have not considered the effects of uncertain information. We acknowledge that uncertainties can exist in calculating M values for time periods with sparse data, and in the selection of and application of counterfactuals, which are assumed to accurately represent the impacted individual.

Desipite its flaws, the *PIM* is a needed step in a larger thrust to help engineers become better at designing products for social impact.

CHAPTER 3. A METHOD OF CREATING FIRST ORDER SOCIAL IMPACT MODELS FOR ENGINEERING

3.1 Introduction

As engineers, the products we design impact society. Sometimes this impact is obvious; the design of a bridge that links two communities, the design of a medical device that extends life or the design of sensors used in warning systems. And sometimes the impact is not obvious; the design of entertainment systems that change family dynamics, the design of machinery that favors a male workforce, the design of hospital ventilation that spreads infection. These represent the social impacts of products, where social impact is defined as how a product changes "on the day-to-day quality of life of persons" [56]. The most obvious social impacts that products have — generally health and employment — are often recognized in the engineering community. In some cases, for these obvious social impacts, engineers are able to create product requirements and performance measures that relate a product's performance to its social impact. Other social impacts, such as family and gender impacts, tend to be attributed less to a product as they may seem unrelated to a product's design. Nevertheless, products can indeed change people's lives in more ways than are generally understood by the engineering community [10]. As a result, engineers are likely designing products without knowing the social impact of design decisions.

Social impact indicators and categories can be used to describe a product's social impact. Social impact indicators are used to know the amount of social impact a product has. Sandhu-Rojon defines indicators as "what we observe in order to verify whether – or to what extent – it is true that progress is being made" [9]. One or more social impact indicators can be chosen to demonstrate the social impact that a product has on a person or group. Social impact indicators can be grouped into social impact categories. In a collaborative work between sociologists and engineers, eleven social impact categories for products were identified [10]. The social impact categories for products they identified are: health and safety, paid work, stratification, civil rights, education, family, gender, population change, conflict and crime, networks and communication, and cultural identity and heritage [10]. We recognize that these social impact categories may seem far removed from an engineer's decisions. Nevertheless, it will be demonstrated in this paper how a product's features can be connected with one or more of these social impact categories, thus allowing the engineer to predict and improve the social impacts of the products they're designing.

Currently, there is a lack of methods that can help an engineer identify, understand, and improve a product's social impacts. A coalition of companies chose 71 social impact indicators to measure the social sustainability and impact of their products [13, 57]. While the companies are able to identify some social impacts using these indicators, many of the indicators are dependent on company policies instead of the products' design. For example, this makes improving and understanding a product's impact more difficult. Under this scenario, design decisions made by the engineer would not change many of the product's social impact indicators. Also, the method of evaluating the indicators is a ranking by self-assessment, which can bias the results. The indicators as identified by the coalition are fundamentally different that what is proposed in this paper; namely that the coalition's impact indicators are self assessments of social impacts, not the measurement of the impact itself.

In a previous work by the authors, a metric was introduced to simplify measuring the social impact of products that are designed to alleviate poverty [58]. This metric measures a product's impact in five categories without attempting to measure all of the impacts that a product might have. While this simplifies the process of measuring a product's impact, some impacts are missed.

While the principles of social impact are most often applied to assessment (defined as the evaluation of impact a posteriori), predictive models of social impact (primarily for use a priori) can also be used. Currently, social scientists use simple first order models to help predict the social impact of new programs or policies [59, 60]. As engineers, we are often tasked with creating models of complex systems. In the models we create, it is common to add emphasis in areas of our expertise, at times unknowingly disregarding other aspects of the system we don't fully understand [61]. Engineers need a method for identifying a product's social impact. Once engineers can identify and understand social impacts, they will be able to create more comprehensive models of a product's social impacts. These models will allow social impact to be explicitly considered during the product development process.

Much can be learned by how social scientists measure the impact of different social programs and government policies. The Handbook on Impact Evaluation by the World Bank details how these difficult impact studies can be done [59]. Though the handbook was created specifically for measuring the social impact of government policies, many principles of measuring and predicting social impact can be applied to products as well. The handbook describes how to use a control group, introduces a simple predictive model, and gives other important information on how to measure and predict the social impacts of programs. The equation introduced by the World Bank to predict the impact of programs is used in the current paper as an example of how first order product social impact models can be created.

The purpose of this paper is to introduce a method of modeling the social impact of any product. In Section 3.2 of this paper, we present the method and in Section 3.3 we use the method to predict the social impact of the border wall between the U.S. and Mexico. The final section provides closing remarks with a description of limitations and future work.

3.2 Method for Modeling the Social Impact of Products

The methodology introduced in this paper is comprised of four steps:

1. Identify a product's users, requirements, and objectives
2. Determine which social impact categories are influenced by the product
3. Select social impact indicators to represent each impact category
4. Create predictive models for the indicators

After completing the steps, the engineer will have the ability to measure and predict a product's social impacts. This process can be completed during the product development process to predict social impact, or after development to evaluate it.

3.2.1 Step 1: Gather Product Development Information

As a first step, the engineer collects product and user information. Specifically, the product developer needs to identify a product's requirements, users, and objectives. This information is

Table 3.1: Social impact categories and some examples of what each category includes.

Impact Category	**Example Areas of Impact**
Health and Safety Impact	Living conditions, mortality
Paid Work Impact	Employment rates, industrial diversification
Stratification Impact	Inequality, social status
Civil Rights Impact	Minority and Human rights
Education Impact	Education, skills
Family Impact	Change in family roles and structure
Gender Impact	Gender roles and equality
Population Change	Transiency of the population, age structure
Conflict and Crime Impact	Crime, civil and domestic conflict
Social Networks and Communication Impact	Personal relationships, social capital
Cultural Identity /Heritage Impact	Values, personality traits

often used by product developers in product development processes. This information tells why the product is useful, who uses it, and what goals the engineer has in creating it.

The information collected in this step helps identify a product's social impacts. A product's requirements clarify what the market and engineer believe the product needs to accomplish to be successful. These requirements can include references to certain impact categories, either explicitly or implicitly.

The product users are another source of information that can help identify impacts. The social impact of a product is a function of the product and the user [58]. Therefore, if the user is not understood, then the social impact of the product cannot be predicted. This also means that products impact users differently depending on their needs. If the user's needs are known, the impact categories related to these needs can be identified as potential impact categories.

During the design process, engineers often create an objective statement that guides design decisions that are made for the product. This objective can answer these questions: what is the product, what problem does it solve, and what is the target market [25]? These statements can lead to social impact categories that are important to the people who designed the product.

Table 3.2: Spearman correlation between different product social impact categories.

	Family	Conflict & Crime	Paid Work	Education	Population Change	Gender	Cultural Identity & Heritage	Networks & Communication	Civil Rights	Stratification
Health & Safety	0.25	-0.33	**-0.50**	-0.48	**0.56**		-0.33	**-0.55**	**0.53**	-0.44
Family					0.49	**0.52**	0.17		0.28	0.27
Conflict & Crime				0.31			0.37	0.48		0.30
Paid Work				0.27	-0.25			**0.50**	-0.28	**0.67**
Education					-0.44	-0.21	0.22	**0.57**		0.36
Population Change						0.31		-0.39	0.32	
Gender							0.30	-0.22		
Cultural Identity & Heritage								0.23		0.25
Networks & Communication										**0.53**
Civil Rights										

Cohen's Standard to Evaluate Association Strength

|0.10-0.29|	Small association
|0.30-0.49|	Moderate association
|**0.50-1.00**|	Large association

3.2.2 Step 2: Determine Social Impact Categories

Once the product development information is collected, the product impact categories are identified. The categories used in this paper are the eleven categories of product impact that have been identified by Rainock et al. [10]. Table 3.1 shows all of the impact categories as well as some examples for each category, which may assist in identifying anticipated impacts.

As a first part of this step, impact categories are selected that best match the product's capabilities. Some impact categories may have a more recognizable relationship with the product's requirements, users, or objectives while other impact categories may be difficult to identify initially. For example, the requirement "the product increases the user's income" most often has a relationship to the impact category Paid Work. However, this requirement may also be related to Population Change, as the product may sustain a job market and provide new employment for many people and increase the local population size. Additionally, user information and product objectives can point towards additional social impact categories.

In the case of users, the user's needs can change a product's social impact. An example of this is the impact of fuel-efficient biomass stoves. Often the most substantial impact of biomass stoves in on the Health and Safety of the user because fuel-efficient biomass stoves reduce harmful indoor emissions. If stoves are designed for user's with additional needs, the impact of the stove may increase. For example, some fuel-efficient biomass cookstoves are designed for displaced, refugee women [62]. These women are often victims of physical and sexual assault while they are collecting firewood. The additional need for increased security enables these stoves to also impact Gender and Conflict and Crime because the user's likelihood of being assaulted decreases. Identifying the less intuitive relationships that a product has with the impact categories in Table

3.1 can be difficult. For this reason, two different methods of determining these impact areas are introduced in the following paragraphs.

In a study done by Ottoson et al., 150 products were assessed for their social impact, using the same impact categories in Table 3.1 [63]. It was found that for the 150 products reviewed, some social impact categories were likely to appear together. Table 3.2 shows correlation between social impact categories. For instance, if it is known that a product will impact Health & Safety, there is a higher potential that it will also impact Paid Work, Stratification, Human Rights, and Family. And that there is a lower potential the product will impact Networks & Communication or Cultural Identity/Heritage. If a social impact category has been identified, Table 3.2 can be used to determine what other categories are likely to be related to the product.

Another method of identifying impact categories uses a set of questions about the product. A series of questions have been created so that an product developer can identify additional impact categories, see Table 3.3. Some of the questions in Table 3.3 are from a booklet that helps product designers consider social issues [64]. These questions help a design team discuss and identify which categories their product may impact and which they should include.

After using Tables 3.2 and 3.3 several impact categories should be identified. During the product development process and as more information is gained the impact categories should be assessed for their relevancy and to ensure that all of the impact categories related to the product are included. Impact indicators may be added or removed based on additional information that is gained throughout the development process.

3.2.3 Step 3: Selecting Social Impact Indicators

Once impact categories are identified, indicators need to be chosen. Indicators are what is measured or predicted in each impact category to understand a product's impact. Sandhu from the United Nations Development Programme stated that "the challenge in selecting indicators is to find measures that can meaningfully capture key changes, combining what is substantively relevant as a reflection of the desired result with what is practically realistic in terms of actually collecting and managing data" [9]. This section can help guide an engineer in selecting indicators that will inform an engineer about a product's impact while following the characteristics introduced by Sandhu.

Table 3.3: Questions that help lead to identifying impact categories

	Questions	Potential Impact Categories
1	Does it encourage a sense of community?	Networks, Cultural Identity
2	How could your design demonstrate the values of the user?	Cultural Identity
3	Does it encourage participation and belonging?	Civil Rights, Networks, Cultural Identity
4	Does it improve health and well-being?	Health and Safety, Stratification
5	Does it encourage empowerment and promote human competence?	Stratification, Education
6	Does it enrich users' lives or increase quality of life?	Health and Safety, Stratification
7	Does it enhance social interaction, communication, and engagement?	Civil Rights, Networks
8	Does it maintain local/cultural traditions?	Cultural Identity
9	Does it help make money?	Paid Work
10	Does it help save time?	Paid Work
11	Does it enhance education?	Education
12	Does it challenge stereotypes?	Family, Gender, Cultural
13	Does it improve personal or communal security?	Health and Safety, Conflict and Crime
14	Does it encourage activism?	Civil Rights, Education, Gender
15	Does it make the community more attractive to outsiders?	Population Change
16	Does it influence inequality in the community?	Stratification, Civil Rights
17	Does it change the user's hireability?	Paid Work, Education
18	Does it change the user's vulnerability?	Gender, Conflict and Crime
19	Does it change the user's role in society or their family?	Civil Rights, Family, Gender
20	Does it bring together or separate families?	Family
21	Does it encourage relocation?	Family, Population Change

There are databanks of hundreds of social impact indicators. The World Bank has compiled a data bank of hundreds of indicators for tracking the progress of countries. Some of the indicator categories the World Bank uses are similar to the social impact categories used in this paper, see Figure 3.1. Table 3.4 shows all of the World Bank's indicator groups, the number of indicators included in each category, and example indicators. Most of the World Bank's indicators are measured at the national level and few, if any, products will have a measurable impact on an entire population. Nevertheless, many of the indicators can be adapted for being used on smaller groups and individuals. Other sources for impact indicators are the Oxford Poverty and Human Development Initiative's Working Papers [29–33, 65]. Each of these articles highlights a social issue that is under-represented in existing data and gives suggestions of impact indicators that could be used to measure the issue at a national level. In the appendix of each article they provide example surveys and indicators that can be used to measure a product's impact. Both of these resources, along with which impact category they are related to, are listed in Table 3.5. Together the World Bank and the Oxford Poverty and Human Development Initiative's Working Papers include hundreds of indicators, but do not give guidance on choosing them. Table 3.5 can help reduce the number of potential indicators to a manageable number.

Once the indicators have been selected, the indicators need to be assessed. First, the indicators should be assessed by impact category to assure that the category is represented sufficiently. The candidate set of indicators should be thoroughly explored. When necessary, impact categories can be added in this stage of the process if a selected indicator is related to a hitherto unidentified impact category.

After each impact category has sufficiently been represented by indicators, the indicators need to be evaluated on how they can be integrated into the product development process. Products are often designed to meet certain product requirements. The extent to which the product meets these requirements can evaluated by performance measures [46]. When the method introduced in this paper is done in parallel with a product development process, indicators and impact categories can be transformed into performance measures. As the initial requirements were used to help find the impact categories, some of the impact categories and indicators may already be requirements and performance measures.

3.2.4 Step 4: Creating Social Impact Models

Product social impact models, as discussed in this paper, are analytical equations that are used to predict the performance of the social impact indicators selected in Section 3.2.3.

The social impact models used for a product are unique to that product and can not be applied to other, dissimilar products. This principle is also true for mechanical stress equations. The equation used to model mechanical stress in a beam changes for different types of forces, boundary conditions, and beam shapes. Similarly, social impact models for products will not be the same from one product or user to another. A product's social impact is a function of the product

Table 3.4: The World Bank's indicator groups and how many indicators are in each category (some indicators are in more than one category).

Indicator Category	Number of Indicators	Example Indicators
Agriculture & Rural Development	47	Employment in Agriculture
Aid Effectiveness	73	Income Share Held By Lowest 20%
Climate Change	80	Nitrous Oxide Emissions
Economy & Growth	261	Household Final Consumption Expenditure
Education	159	Educational Attainment of the Population
Energy & Mining	50	Access to Electricity
Environment	112	Plant Species Threatened
External Debt	229	Average Interest on New Debt Commitments
Financial Sector	85	Accounts at a Financial Institution
Gender	161	Children Out of School (Male, Female)
Health	207	Prevalence of HIV
Infrastructure	51	Railway Passengers
Poverty	25	GINI Index, Poverty Gap
Private Sector	173	Time Required to Start a Business
Public Sector	97	Internally Displaced People
Science & Technology	13	Researchers in R&D, Patent Applications
Social Development	31	Children in Employment, Refugee Population
Social Protection & Labor	151	Employment in Agriculture
Trade	152	Goods or Services Imports and Exports
Urban Development	22	Mortality Caused by Road Traffic Injury

Table 3.5: Resources for selecting indicators.

Source	**Resource**	**Impact Categories**
The World Bank	Health	Health & Safety
	Private Sector	Paid Work
	Social Protection and Labor	Paid Work
	Poverty	Stratification
	Urban Development	Stratification
	Agriculture and Rural Development	Stratification
	Education	Education
	Gender	Gender
OPHI Working Papers	Physical Safety and Security	Health & Safety, Crime & Conflict
	Psychological and Subjective Well-being	Health & Safety
	Employment	Paid Work
	Agency and Empowerment	Paid Work, Gender
	The Ability to Go About Without Shame	Stratification
	Social Isolation	Civil Rights, Family, Networks & Communication

and the user, where the social impact of a product, I, is,

$$I = f(U, P) \tag{3.1}$$

where f is the function that calculates a product's social impact, U represents user parameters, and P represents product parameters [58]. The social impact of a car demonstrates this relationship as the social impact of a car, is dependent on the ability of the driver, the needs of the driver, the infrastructure around the driver, and the car design.

The basic form of the equation that is currently used by social scientists to evaluate the social impact of programs using impact indicators is,

$$Y = \alpha * X + T * \beta + \varepsilon \tag{3.2}$$

where Y is the final indicator value, α is the initial indicator value, X is other relevant parameters of the individual for whom the social impact is being measured, T is a dummy variable (0 or 1) for differentiating between people or groups who are impacted by the product or not, β is the program's impact to the indicator value, and ε is an error term for unobserved factors that effect Y [59]. Equation 3.2 has been used for evaluations as well as predictions [60]. In this paper the variables T and X from Equation 3.2 are not used here because two groups of users and non-users are not compared, as the wall will span the entire U.S.–Mexico border.

The β term is the most difficult term in Equation 3.2 to determine. The approach used in this paper is to find an existing relationship between the impact indicator and product parameter that can be measured or predicted. For example, the extent to which a product improves safety in a community could be a function of how many crimes are committed. If the product reduces the number of criminal acts, such as would be the case security cameras or lighting, the impact the product has on crime rates can be extrapolated.

After indicators are predicted, the impact that the product has on the indicator value can be found. One method of doing this is called difference-in-differences [48]. This method measures the difference between an impacted group and control group. Using this method, the impact of a product, I, is,

$$I = Y_T - Y_C \tag{3.3}$$

where Y_T is the final indicator value for someone who was impacted by a product and Y_C is the final indicator value for a control, someone who did not have the product. Measuring impact this way accounts for how people are able to improve their lives without the product as well as any other factors that may be change a product's impact.

Once additional information is obtained and greater accuracy is needed, higher fidelity models can be used. Such models could be non-linear, multi-variable, or other forms, depending on the indicator. While these models can be more accurate, they may also need additional variables or higher data collection rates and quality.

Creating accurate models requires the product developer to understand all of the factors that affect the indicators. In most cases, the product is only one part of the reason why indicators are changing. Before models are created, the user and their social environment should be understood enough to know what these factors are. These factors may include government policies, development programs, family roles and dynamics, cultural practices, economic status, social class, and community behaviors. Understanding these factors and making an effort to have them integrated into the models will make them more accurate.

3.3 Predicted Social Impact of the U.S.–Mexico Border Wall

The example in this paper is a social impact prediction study for the proposed expansion of the U.S.–Mexico Border Wall (UMBW). In this example, the method introduced in this paper is implemented to identify product development information, impact categories, indicators, integrate with the design process, create predictive models, and make predictions for the selected impact indicators. All of the models created in the examples follow the general form given in Equation 3.2.

The U.S.–Mexico border Wall is an immense physical product that impacts the lives of Americans, Mexicans, and other immigrants hoping to enter or leave the United States. Currently, the U.S.–Mexico border has an intermittent wall, fencing, and vehicle barricades for 580 miles of the 1,989-mile border. The current U.S. presidential administration has proposed building a formidable wall along more portions of the border in hopes of reducing the number of illegal immigrants entering the United States [66]. Several articles have already been published on the environmental impacts of such a wall [67–70]. In this paper, we will focus on how the social impact of an expanded border wall can be predicted and improved.

3.3.1 Step 1: Gather Product Development Information

The product development information was collected from a solicitation for building contractors to build border wall prototypes [71], a fact sheet on the wall and immigration policies from the White House [72], a Customs and Border Protection Roundtable [73], and an executive order from President Trump [66].

- Users
  1. Communities close to the UMBW
  2. Illegal Immigrants
  3. Border Patrol Officers
- Requirements
  1. The wall is at least 18 feet high
  2. The wall difficult to climb over
  3. The wall includes anti-climb features
  4. The wall prevents digging 6 feet under the wall
  5. The wall resists breaching by hand tools (such as sledgehammers, battery operated impact and cutting tools, oxy/acetylene torch, and other similar hand-held tools) for at least 30 minutes but ideally for over 4 hours
  6. The wall is aesthetically pleasing from the U.S. side
  7. The wall accommodates drainage
  8. The wall includes sliding gates for authorized pedestrians and vehicles
  9. The wall can be built on a 45% slope
  10. The wall is cost effective to build, maintain, and repair

Table 3.6: The social impact categories and their determined relationship with the UMBW.

Impact Categories	**Relationship to the UMBW**
Health and Safety Impact	Question 20: Impact personal or communal security
Paid Work Impact	Objective: Support Border Wall Officers
Stratification Impact	*Not related to the UMBW*
Civil Rights Impact	Question 13: Enhance social interaction, communication, and engagement
Education Impact	*Not related to the UMBW*
Family Impact	Question 7: Potential to separate families
Gender Impact	*Not related to the UMBW*
Population Change	Objective: Prevent illegal immigration
Conflict and Crime Impact	Objective: Prevent infiltration of criminals
Social Networks and Communication Impact	*Not related to the UMBW*
Cultural Identity/ Heritage Impact	*Not related to the UMBW*

11. The wall includes see-through portions

- Objective

1. Support the border patrol, decrease illegal immigration, and prevent infiltration by cartels criminals, traffickers, smugglers, and threats to both public safety and national security.

3.3.2 Step 2: Identify Impact Categories

Using the product development information, all but three impact categories were determined to be unrelated to the product. The three impact categories that are related to the product are Conflict & Crime, Population Change, and Paid Work. After these impact categories were identified, the questions in Table 3.3 were used to determine if the wall has other impact categories that were not directly addressed in the product development information. Table 3.6 shows how each impact category is related to the UMBW.

3.3.3 Step 3: Selecting Indicators

The indicators that were chosen to assess the impact of the U.S.–Mexico border wall were chosen for their ability to represent each impact category and be influenced by the wall's parameters and features. Indicators were chosen for each impact category because of their ability to represent the relationships between the impact categories and the product, see Table 3.6. The impact indicators, organized by impact categories, are:

Crime & Conflict:

$n_Arr.$ Number of arrested illegal immigrants at the border

$n_{\text{Att.}}$ Number of attacks on Border Patrol

$n_{\text{Crim.}}$ Number of criminals arrested that are illegal immigrants

r_{Crime} Crime rate near the border wall

p_{Border} Percent of arrested illegal immigrants who came through the border

n_{Enter} Number of illegal immigrants crossing the border

Population Change:

$n_{\text{Arr.}}$ Number of arrested illegal immigrants at the border

Paid Work:

$n_{\text{Off.}}$ Number of border patrol officers

n_{Work} Number of illegal immigrants in U.S. workforce

c_{Border} Annual spending on U.S.–Mexico border

Family:

n_{Children} Number of children sent across the border illegally

$n_{\text{Fam.}}$ Number of families separated as a result of illegal immigration

Civil Rights:

n_{Court} Number of illegal immigration court cases

t_{Court} Trial time of illegal immigration court cases

Health & Safety:

$n_{\text{Att.}}$ Number of attacks on Border Patrol

n_{Deaths} Number of deaths of illegal immigrants crossing the border

The indicators for the UMBW were selected from the resources in Table 3.5 as well as anticipated impacts identified by the current presidential administration [73].

3.3.4 Step 4: Creating Models

The requirements and performance measures created from the impact categories and impact indicators are:

The wall reduces crime:

Number of arrested illegal immigrants at the border

Number of attacks on Border Patrol

Number of criminals arrested that are illegal immigrants

Crime rate in countries along border wall

% of illegal immigrants who came through the border

Number of illegal immigrants crossing the border

The wall improves the safety of the Border Patrol and immigrants:

Number of deaths of illegal immigrants crossing the border

Number of children sent across the border illegally

Number of attacks on Border Patrol

The wall helps the American workforce:

Number of border patrol officers

Annual spending on U.S.–Mexico border

Number of illegal immigrants in U.S. workforce

The wall reduces illegal immigration:

Number of illegal immigrants crossing the border

% of illegal immigrants who came through the border

Number of families separated as a result of illegal immigration

The wall has no effect on the civil rights of immigrants:

Number of illegal immigration court cases

Trial time of illegal immigration court cases

Some impact indicators are included in more than one requirement. This is common, performance measures often influence many requirements. Models were created for each performance measure to know how different product features can affect the UMBW's impact. In the following equations, the subscript $[\,]_i$ is for the current value of the indicator and the $[\,]_f$ subscript is for the predicted value of the indicator.

For the requirement, the wall reduces crime, the model for predicting the number of arrested illegal immigrants at the border, $n_{f_{\text{Arr.}}}$, is,

$$n_{f_{\text{Arr.}}} = n_{i_{\text{Arr.}}} + [n_{i_{\text{Arr.}}} k_{\text{Change}} (\frac{k_{\text{Cross}} k_{\text{Sec.}}}{k_{\text{Change}}} - k_{\text{Cross}} k_{\text{Sec.}} - 1)] \tag{3.4}$$

The improved security factor of the new wall, $k_{Sec.}$, is,

$$k_{Sec.} = \frac{t_{i_{Cross}}}{t_{f_{Cross}}} \tag{3.5}$$

where $t_{i_{Cross}}$ is the current time for someone to climb over the current barriers at the border and $t_{f_{Cross}}$ is how long it takes to cut through or climb over the new border wall. This may change for different sections of the border as some of the border already has a fence or barrier. This factor is a measure of how much more time it takes to cross the border with the expanded UMBW design.

The model for the number of attacks on border patrol officers, $n_{f_{\text{Att.}}}$, is

$$n_{f_{\text{Att.}}} = n_{i_{\text{Att.}}} + [n_{i_{\text{Att.}}} \frac{l_{f_{\text{Wall}}}}{l_{i_{\text{Wall}}}} (1 - n_{f_{\text{Sec.}}}) \frac{n_{f_{\text{Off.}}}}{n_{i_{\text{Off.}}}}] \tag{3.6}$$

The number of attacks on border patrol officers is a function of the wall's security as well as the length of the wall and the number of officers.

The model for the number of arrested criminals, $n_{f_{\text{Crim.}}}$ is,

$$n_{f_{\text{Crim.}}} = n_{i_{\text{Crim.}}} - [n_{i_{\text{Crim. Ill.}}}(k_{\text{Sec.}} - k_{\text{Change}})\frac{n_{\text{Enter Border}}}{n_{\text{Enter}}}] \tag{3.7}$$

As this one of the primary objectives of the wall, it should be related to the improved security of the wall, $k_{\text{Sec.}}$. It is anticipated that over time, the number of criminals that are illegal immigrants will decrease as fewer illegal immigrants are entering the country as a result of the wall.

The model for the crime rate in counties along border wall, $r_{\beta\text{Crime}}$, is,

$$r_{f_{\text{Crime}}} = r_{i_{\text{Crime}}} - [r_{i_{\text{Crime Ill.}}} k_{\text{Sec.}} k_{\text{Cross}}] \tag{3.8}$$

As these counties are nearest to the border wall they should be impacted greatly by the wall. Though, their crime rate will only possibly drop by how much of the crime is committed by illegal immigrants who crossed the border.

The model for the percent of arrested illegal immigrants who came through the border, $p_{\beta\text{Ill. Border}}$, is,

$$p_{f_{\text{Border}}} = p_{i_{\text{Border}}} - [p_{i_{\text{Border}}} k_{\text{Sec.}} k_{\text{Change}}] \tag{3.9}$$

The percent of illegal immigrants who come through the border is dependent on how effective the wall is at keeping illegal immigrants out as well as how many will enter the country by another way.

The model for the number of illegal immigrants entering the country, $n_{f_{\text{Enter}}}$, is,

$$n_{f_{\text{Enter}}} = n_{i_{\text{Enter}}} + [n_{i_{\text{Enter Border}}}(1 - k_{\text{Change}} - k_{\text{Sec.}}(1 - k_{\text{Change}})k_{\text{Cross}})] \tag{3.10}$$

The impact that the wall has on illegal immigration is dependent on how effective the wall is and how often people change their method of getting into the country.

The model for the performance measure, the number of children that are sent alone to cross the border illegally, $n_{f_{\text{Children}}}$, is

$$n_{f_{\text{Children}}} = n_{i_{\text{Ill. Children}}} - [n_{i_{\text{Ill. Children}}} k_{\text{Cross}} k_{\text{Sec.}}] \quad (3.11)$$

This performance measure came directly from the discourse that President Trump had at a Border Protection Roundtable, as it was mentioned that the wall could help these children who cross the border alone and sometimes die on their way [73]. Currently, the wall doesn't have features or parameters that can directly change how many children are sent across the border. This is another indicator that suggests the social impact of the wall can be improved.

The first performance measure for the requirement, the wall improves the safety of the border patrol and immigrants, is the number of illegal immigrants who die crossing the border, $n_{f_{\text{Deaths}}}$. The model for this performance measure is,

$$n_{f_{\text{Deaths}}} = n_{i_{\text{Deaths}}} - [n_{i_{\text{Deaths}}} k_{\text{Cross}} k_{\text{Sec.}}] \quad (3.12)$$

As less people attempt to cross the border, less people will die on the trip across the border. If one of the wall's features was designed to further decrease the number of deaths of illegal immigrants, such as cameras or call stations, then this model would change.

The model for the performance measure, the number of families separated as a result of illegal immigration, $n_{f_{\text{Fam.}}}$, is

$$n_{f_{\text{Fam.}}} = n_{i_{\text{Fam.}}} - [n_{\text{Fam.}} k_{\text{Return}} k_{\text{Sec.}}] \quad (3.13)$$

As less people are able to cross the border and people return to their families, less families will be split across borders.

The first performance measure for the requirement, the wall helps the American workforce, is the number of border patrol officers, $n_{f_{\text{Off.}}}$.

$$n_{f_{\text{Off.}}} = n_{i_{\text{Off.}}} - [n_{i\text{Off.}} k_{\text{Replace}} k_{\text{Sec.}}] \quad (3.14)$$

A border wall would impact the number of border patrol officers. As the wall deters illegal immigrants, the need for border patrol officers will decrease. The rate that border patrol officers are replaced by the wall, k_{Replace}, is a measure of how many officers are needed after the wall is built. As the wall's security is high, less officers are needed. Automation of sensors and alarms could further decrease the number of officers that are needed at the border.

The model for the performance measure, the annual spending on the U.S.–Mexico border, $c_{f_{\text{Border}}}$, is

$$c_{f_{\text{Border}}} = c_{i_{\text{Border}}} + [n_{\text{Off. New}} c_{\text{Off.}} + c_{\text{Repair}} n_{\text{Repair}}] \tag{3.15}$$

The cost and number of wall repairs per year are directly linked to the design and material selection of the wall.

The model for the performance measure, the number of illegal immigrants in the U.S. workforce, $n_{f_{\text{Work}}}$, is

$$n_{f_{\text{Work}}} = n_{i_{\text{Work}}} - [n_{i_{\text{Work}}} k_{\text{Sec.}} k_{\text{Cross}} + n_{i_{\text{Work}}} k_{\text{Change}}] \tag{3.16}$$

The number of illegal workers will be affected by the ability for them to enter the country.

The first performance measure for the requirement, the wall has no effect on the civil rights of immigrants, is the number of illegal immigration court cases, $n_{f_{\text{Court}}}$. The model for this performance measure is,

$$n_{f_{\text{Court}}} = n_{i_{\text{Court}}} + [n_{i_{\text{Court}}} \frac{k_{\text{Arrest}}}{k_{\text{Return}}} k_{\text{Sec.}}] \tag{3.17}$$

As the wall assists border patrol arrest more illegal immigrants, the number of court cases will increase while, as illegal immigrants return to their families, the number of court cases decreases. But, the wall cannot affect the number of arrests that are not at the border. This is captured in k_{Arrest}.

The last indicator is the trial time of illegal immigration court cases, $t_{f_{\text{Ill. Court}}}$. The model for this performance measure is,

$$t_{f_{\text{Court}}} = t_{i_{\text{Court}}} + [t_{i_{\text{Court}}} k_{\text{Arr. New}} k_{\text{Sec.}}] \tag{3.18}$$

As more people are arrested, the time for court cases will increase.

Figure 3.1: One of the prototypes built for the UMBW.

3.3.5 Predictions

In order to make predictions for the social impact of the UMBW, a design has to be selected for which to make predictions. The design used to make predictions in this paper is the least expensive prototype of those that were built near the San Diego border. It is composed of a concrete foundation with steel tubes for the first half of the wall and a top section made from concrete, see Figure 3.1. As we are not testing the wall, we will assume that it meets all of the constraints for time to cut through the wall or climb over the wall. The predictions that have been made for this wall design can be seen in Table 3.7.

In order to use the indicator values in decision making or optimization, the indicators can be combined into a single value. While this may not allow for a deep understanding of the product's impact, it is useful for comparing product options or different design parameters. Table 3.8 shows the results of an approach of combing the social impact indicator values for the UMBW. This approach is similar to what the UN uses in several of their metrics such as the Human Development Index and the Multidimensional Poverty Index [74, 75]. First, indicators are normalized by calculated the percent change, P, of each indicator. Then, the indicators are grouped into their impact categories, C. The average value of each category $\bar{C}$ is calculated and used to calculate the total impact, I_T,

$$I_T = \sum_{i=1}^{n} \frac{\bar{C}_i}{n} \tag{3.19}$$

This I_T value is the average percent change to all of the impact indicators where a positive value is a positive impact and a negative value is a negative impact.

Deciding whether the impact of the U.S.–Mexico border wall is positive or negative is not simple. For any product, there can be positive and negative impacts for each impacted group. Table 3.7 shows the impact the border wall would have for each indicator. The negative and positive values are not for positive or negative impact, but rather if the indicator value increased or decreased. Determining if an increase or decrease is a positive or negative impact is often dependent on the stakeholder.

We predict that the wall will decrease the number of illegal immigrants who enter the country through the border on foot. But, at the same time, more people will enter the U.S. through other ways, such as overstaying non-immigrant visas. Currently, more people enter the country illegally by overstaying visas than crossing the border on foot [76]. It is predicted that a border wall would increase the rate that illegal immigrants enter the country by other means. Also, it is predicted that the border wall will have some negative impacts on Border Patrol officers. We predict that the number of assaults on Border Patrol will increase slightly and the number of border patrol officers will decrease as the wall can do the work of many officers. Even so, the spending on the border will increase. As border officers are laid off, the costs of maintaining the wall will replace the cost of the laid-off officers. Illegal immigrants will be negatively impacted by the border wall. Less illegal immigrants will be able to enter the country through the border, which will make entering the country more difficult. As illegal immigrants find a new method of entering the country, more of them will be arrested by Immigration and Customs Enforcement (ICE) officers than border patrol officers. ICE arrests most often go to court, which means that the number of illegal immigration court cases will increase.

By knowing what the impacts of the wall are on immigrants, border patrol, and local communities, the impact of the wall could be improved. Table 3.8 shows that we predict wall would Overall positively impact Border Patrol and the communities near the wall, but would negatively impact illegal immigrants.

Table 3.7: Predictions for the UMBW indicators using equations 4-17.

Indicator	Current	Prediction	Impact
$n_{\text{Arr.}}$	408,870	145,976	-262,894
$n_{\text{Att.}}$	439	524	85
$n_{\text{Crim.}}$	67,742	63,352	-4,390
r_{Crime}	2,838	2,486	-352
p_{Border}	29.7%	17.9%	-11.8%
n_{Enter}	418,990	357,323	-61,666
n_{Children}	59,692	32,787	-26,905
n_{Deaths}	322	177	-145
$n_{\text{Fam.}}$	150,000	110,492	-39,508
$n_{\text{Off.}}$	17,026	8,740	-8,286
c_{Border}	$30.8 million	$32.3 million	$1.53 million
n_{Work}	8,050,000	7,239,102	-810,898
n_{Court}	228,454	229,446	992
t_{Court}	1000	435	-565

Table 3.8: Synthesizing the social impact data for each stakeholder group.

	Without Checkpoints and Sensors		With Checkpoints and Sensors	
Method	Border Patrol and Communities	Illegal Immigrants	Border Patrol and Communities	Illegal Immigrants
Average	0.257	-0.103	0.303	-0.057

Social impact indicators can help the engineer know what product features could improve the impact on all stakeholders. The indicator, deaths along the U.S.–Mexico border, n_{Deaths}, negatively impact all of the stakeholder groups. By installing sensors and cameras to find the immigrants that are in the direst need as well as checkpoints along the wall with supplies for desperate immigrants, the social impact is improved for all stakeholder groups, see Table 7.

3.4 Concluding Remarks

Creating social impact models requires the engineer to be well informed of the factors that are affecting the indicators. Most often, the product is not the only influence that is changing indicator values. This can be seen with the U.S.–Mexico border wall. The indicators related to Civil Rights are also impacted by government policies regarding the rights of illegal immigrants. In fact, the wall's construction, maintenance, staffing, and completion are all impacted by government policies. This is true for many other products as well. Medical devices, automobiles, and buildings are all subject to changing government regulations that may change their social impact models. As new policies are made, the social impact models that are affected should be updated.

Some of the factors that are created in the initial models may change. Many of the models for the U.S.–Mexico border wall use a factor called the improved security factor, $k_{\text{Sec.}}$. This is meant to measure how much more effective the border wall is at inhibiting people from crossing the border. This is possible to measure by testing different methods of going over, under, and through the wall. While this is a measured value, it is possible that the same term will not be used to predict several performance requirements. As more information is collected, the models should be updated.

Finally, models should be created for what needs to be modeled, not simply what we believe to be possible to model. Simple models, such as the models used in this paper, are most likely what will be used to predict the impact at first. If no models are made for an indicator, then important impact information will be lost. Simple social impact models can be used to improve a product's design. Using simple models for the US Mexico border wall, an indicator that can improve the impact for all stakeholders was found. This indicator was used to find new features improve the border wall's social impact. Instead of focusing on creating models that are perfectly accurate, it is more important that they are useful [77].

Often social impact is depicted as a complex problem that cannot be constrained in a way that is usable for engineers. In this paper, it is shown that models can be created that can predict the social impact of an engineered product. By starting the process in this paper with information that engineers often already use in product development processes, this new process can be completed concurrently with traditional product development processes. By implementing the method introduced in this paper with an existing product development process, an engineer can have social impact indicators as performance measures alongside traditional engineering performance measures. This will enable an engineer to possibly optimize a design based on both the functional performance and its social performance.

As this paper simply introduces a method of modeling a product's social impacts, there is future work to be done. First, dealing with the uncertainty of these models is a challenge. This was not addressed in this paper, but each of the indicator values has uncertainty. Second, more complex models of product social impact should be explored. As Equation 3.2 is a common method used by social sciences to predict the impact of social programs, it was used in this paper. Engineering models often use more complex models to predict the performance of a design. New visualization, data collection, and prediction techniques could allow product impact predictions to use more complex models as well. As a product's impact is dependent on the user and the product, see Equation 3.1, relationships between the user's initial conditions and a product's impact also need to be explored.

CHAPTER 4. CONCLUSION

This research is a beginning of an effort to measure and predict the social impacts of engineered products. Using the metric created in this research, an engineer can measure or predict the social impact of a product. The models that are created are simple first order social impact models. Further research can be done on how these models could be improved. These models may be higher order models or take other forms. The research in this thesis has focused on translating a qualitative social impact into a quantitative metric or indicator. Further research on how engineers might use subjective social impact data to improve a product's social impact could further advance this research.

Another finding of this research is that the impact of a product is dependent on the product as well as the user. This can make finding a product's impact more difficult as the impact changes between different users. While this is understood in this research, how a user's conditions and parameters change a product's impact is not understood. Further research can be done on what the important user parameters are that most influence a product's impact. This could help engineers know how to change product parameters or use principles from flexible product design to improve the social impact for all users. By having a flexible design, the impact could be more constant through different users.

In order to understand what a measured or predicted social impact value means, contextual information must also be given. The importance of contextual information can be seen in how evaluations of mechanical stress are done. If a value of stress for a beam is given without knowing the material properties, it is near impossible to determine if the beam will fail or not. Ultimate stress, fatigue stress, and other contextual information about the beam must be known. In this research, the synthesized social impact value, such as the PIM, was compared to another impact, simply gaining employment. This comparison was able show that the product has both positive and negative impacts. While this method can compare two or more impacts, if a product's social impacts were compared to social impact limits, in the same way that a predicted stress is compared to ultimate and fatigue stress, then the engineer could know if the impact value is good or bad. Currently, judging the social impact value is subjective.

REFERENCES

[1] UN/DESA, UNCTAD, ECA, ECE, ECLAC, ESCAP, ESCWA, and UNWTO, 2016. *World Economic Situation and Prospects 2016*. 1

[2] National Academy of Engineering, 2008. Grand Challenges for Engineering. 1

[3] George, C., and Shams, A., 2007. "The challenge of including customer satisfaction into the assessment criteria of overseas service-learning projects". *International Journal for Service Learning in Engineering, Humanitarian Engineering and Social Entrepreneurship,* **2**(2). 1, 5, 27

[4] Sovacool, B. K., and Dworkin, M. H., 2015. "Energy justice: Conceptual insights and practical applications". *Applied Energy,* **142**, pp. 435–444. 1, 5

[5] Thacker, K. S., Barger, M., and Mattson, C. A., 2014. "A global review of end user needs: Establishing the need for adaptable cookstoves". In Global Humanitarian Technology Conference (GHTC), 2014 IEEE, IEEE, pp. 649–658. 1, 5

[6] MacCarty, N. A., and Bryden, K. M., 2016. "An integrated systems model for energy services in rural developing communities". *Energy,* **113**, pp. 536–557. 2, 5

[7] Bovea, M. D., and Vidal, R., 2004. "Increasing product value by integrating environmental impact, costs and customer valuation". *Resources, Conservation and Recycling,* **41**(2), pp. 133–145. 2, 5

[8] Mulugetta, Y., 2005. *Energy for rural livelihoods: a framework for sustainable decision making*. Intermediate Technology. 2, 5

[9] Sandhu-Rojon, R., 2003. "Selecting Indicators for impact evaluation". *UNDP, viewed,* **7**, p. 2004. 2, 30, 35

[10] Rainock, M., Everett, D., Pack, A., Dahlin, E. C., and Mattson, C. A., 2018. "The social impacts of products: a review". *Impact Assessment and Project Appraisal*, pp. 1–12. 2, 30, 31, 34

[11] The World Bank, 2016. *World Development Indicators 2016*. World Bank Publications. 3

[12] George, C., 2012. "Is the Community Partner Satisfied?". *Service-Learning in the Computer and Information Sciences: Practical Applications in Engineering Education*, pp. 517–530. 3

[13] Sustainability, P., 2016. "Handbook for product social impact assessment". *Le Amersfoort: PR{é}*. 3, 31

[14] Becker, H. A., 2001. "Social impact assessment". *European Journal of Operational Research,* **128**(2), pp. 311–321. 3

[15] Mair, J., and Noboa, E., 2006. "Social entrepreneurship: How intentions to create a social venture are formed". In *Social entrepreneurship*. Springer, pp. 121–135. 4

[16] Hutchins, M. J., Gierke, J. S., and Sutherland, J. W., 2009. "Decision making for social sustainability: A life-cycle assessment approach". In Technology and Society, 2009. ISTAS'09. IEEE International Symposium on, IEEE, pp. 1–5. 4

[17] Woodcraft, S., Hackett, T., and Caistor-Arendar, L., 2011. *Design for social sustainability: A framework for creating thriving new communities*. Future Communities. 4

[18] Ma, J., and Kremer, G. E. O., 2015. "A Modular Product Design Method to Improve Product Social Sustainability Performance". In ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, pp. V004T05A053—-V004T05A053. 4

[19] Lee, E. J., and Schwab, K. J., 2005. "Deficiencies in drinking water distribution systems in developing countries". *Journal of water and health,* **3**(2), pp. 109–127. 4

[20] Bruce, N., Perez-Padilla, R., and Albalak, R., 2000. "Indoor air pollution in developing countries: a major environmental and public health challenge". *Bulletin of the World Health Organization,* **78**(9), pp. 1078–1092. 4

[21] Sagar, A. D., 2005. "Alleviating energy poverty for the world's poor". *Energy Policy,* **33**(11), pp. 1367–1372. 4

[22] Grantham-McGregor, S., Cheung, Y. B., Cueto, S., Glewwe, P., Richter, L., Strupp, B., Group, I. C. D. S., and Others, 2007. "Developmental potential in the first 5 years for children in developing countries". *The lancet,* **369**(9555), pp. 60–70. 4

[23] UNICEF, 2015. "The State of the World's Children 2015: Reimagine the Future: Innovation for Every Child". *New York: UNICEF*, pp. 29–115. 4, 21

[24] Rogers, E. M., 2010. *Diffusion of innovations*. Simon and Schuster. 5

[25] Wood, A. E., and Mattson, C. A., 2016. "Design for the Developing World: Common Pitfalls and How to Avoid Them". *Journal of Mechanical Design,* **138**(3), p. 31101. 5, 33

[26] Beno\^\it, C., 2010. *Guidelines for social life cycle assessment of products*. UNEP/Earthprint. 5

[27] Programme), U. U. N. D., 2010. Human Development Report 2010. 6

[28] Alkire, S., 2007. "The missing dimensions of poverty data: Introduction to the special issue". *Oxford development studies,* **35**(4), pp. 347–359. 6, 9

[29] ANA LUGO, M., 2007. "Employment: A Proposal for internationally comparable indicators". *Oxford Development Studies,* **35**(4), pp. 361–378. 6, 36

[30] Diprose, R., 2007. "Physical Safety and Security: A Proposal for Internationally Comparable Indicators of Violence I am grateful for the comments and inputs of Sabina Alkire, Proochista Ariana, Afsan Bhadelia, Alex Butchart, Anna Hiltunen, Mar{\'\i}a Ana Lugo, Andrew Mack, L". *Oxford Development Studies,* **35**(4), pp. 431–458. 6, 36

[31] Ibrahim, S., and Alkire, S., 2007. "Agency and Empowerment: A Proposal for Internationally Comparable Indicators Solava Ibrahim, University of Cambridge, Cambridge, UK. Sabina Alkire, University of Oxford, Oxford, UK. We are grateful for the comments of Valery Chirkov, Ed Deci, Mridul Eapen". *Oxford development studies,* **35**(4), pp. 379–403. 6, 36

[32] Samman, E., 2007. "Psychological and Subjective Well-being: A Proposal for Internationally Comparable Indicators Sabina Alkire, Tania Burchardt, Laura Camfield and Geeta Kingdon provided detailed comments on a draft of this article. I am also grateful for the input of Prooc". *Oxford Development Studies,* **35**(4), pp. 459–486. 6, 36

[33] Zavaleta Reyles, D., 2007. "The Ability to go about Without Shame: A Proposal for Internationally Comparable Indicators of Shame and Humiliation I am grateful for the comments of Sabina Alkire, David Harder, Linda Hartling, Tom de Herdt, Jaqui A. Goldin and Luis Alberto Quiroga on t". *Oxford Development Studies,* **35**(4), pp. 405–430. 6, 36

[34] Peña-Garc\'\ia, A., Hurtado, A., and Aguilar-Luzón, M. C., 2015. "Impact of public lighting on pedestrians' perception of safety and well-being". *Safety science,* **78**, pp. 142–148. 8

[35] Painter, K., 1996. "The influence of street lighting improvements on crime, fear and pedestrian street use, after dark". *Landscape and urban planning,* **35**(2), pp. 193–201. 8

[36] Alkire, S., and Santos, M. E., 2010. "Acute multidimensional poverty: A new index for developing countries". *United Nations development programme human development report office background paper*(2010/11). 9

[37] Billig, P., Bendahmane, D., and Swindale, A., 1999. *Water and sanitation indicators measurement guide*. Food and Nutrition Technical Assistance Project, Academy for Educational Development. 10, 14

[38] for Disease Control, C., Prevention, and Others, 2000. "CDC growth charts for the United States: methods and development". *Series report,* **11**, p. 201. 10, 11

[39] Levitt, S. D., 2004. "Understanding why crime fell in the 1990s: Four factors that explain the decline and six that do not". *The Journal of Economic Perspectives,* **18**(1), pp. 163–190. 16

[40] Edgar, J. M., McInerney, W. D., and Mele, J. A., 2013. *The Use of Locks in Physical Crime Prevention: National Crime Prevention Institute*. Elsevier. 16

[41] Welsh, B. C., and Hoshi, A., 2002. "5 Communities and crime prevention". *Evidence-based crime prevention,* **165**. 16

[42] Barslund, M., Rand, J., Tarp, F., and Chiconela, J., 2007. "Understanding victimization: the case of Mozambique". *World Development,* **35**(7), pp. 1237–1258. 16

[43] Andresen, M. A., 2011. "Estimating the probability of local crime clusters: The impact of immediate spatial neighbors". *Journal of Criminal Justice,* **39**(5), pp. 394–404. 16

[44] Sen, A., 1981. *Poverty and famines: an essay on entitlement and deprivation*. Oxford university press. 17

[45] Alkire, S., and Santos, M. E., 2014. "Measuring acute poverty in the developing world: Robustness and scope of the multidimensional poverty index". *World Development,* **59**, pp. 251–274. 17

[46] Mattson, Christopher A and Wood, Amy E and Renouard, J., 2017. "Village Drill: A Case Study in Engineering for Global Development, With Five Years of Data Post Market-Introduction". *Journal of Mechanical Design,* **In Press**. 18, 37

[47] Khandker, S. R., Koolwal, G. B., and Samad, H. A., 2009. *Handbook on impact evaluation: quantitative methods and practices*. World Bank Publications. 19, 21

[48] Gertler, P. J., Martinez, S., Premand, P., Rawlings, L. B., and Vermeersch, C. M. J., 2011. *Impact evaluation in practice*. World Bank Publications. 20, 39

[49] Hanington, B., and Martin, B., 2012. *Universal methods of design: 100 ways to research complex problems, develop innovative ideas, and design effective solutions*. Rockport Publishers. 20

[50] Amin, M., Kuntchev, V., and Schmidt, M., 2015. "Gender inequality and growth: the case of rich vs. poor countries". *World Bank Policy Research Working Paper*(7172). 21

[51] Mattson, C. A., and Wood, A. E., 2014. "Nine principles for design for the developing world as derived from the engineering literature". *Journal of Mechanical Design,* **136**(12), p. 121403. 21

[52] IBGE, 2016. Cidades@: Itacoatiara, Amazonas. 22

[53] Muir, J. A., 2012. "Indicators of Fertility Change in a Developing Nation: Examining the Impact of Motorcycles as a Distance Demolishing Technology on Fertility Change in Rural Indonesia". 22, 24

[54] de Vasconcellos, E. A., 2013. "Road safety impacts of the motorcycle in Brazil". *International journal of injury control and safety promotion,* **20**(2), pp. 144–151. 22, 24

[55] Jones, T., and de Azevedo, L. N., 2013. "Economic, social and cultural transformation and the role of the bicycle in Brazil". *Journal of Transport Geography,* **30**, pp. 208–219. 24

[56] Burdge, R. J., 2004. *A Community Guide to Social Impact Assessment*, 3rd. ed. Dog Eared Pub. 30

[57] Traverso, M., Bell, L., Saling, P., and Fontes, J., 2016. "Towards social life cycle assessment: a quantitative product social impact assessment". *The International Journal of Life Cycle Assessment*, pp. 1–10. 31

[58] Stevenson, P. D., Mattson, C. A., Bryden, K. M., and MacCarty, N. A., 2017. "Towards a Universal Social Impact Metric for Engineered Products That Alleviate Poverty". In ASME 2017 International Design Engineering Technical Conferences and Computers and Information in

Engineering Conference, American Society of Mechanical Engineers, pp. V02BT03A014—-V02BT03A014. 31, 33, 39

[59] Khandker, S. R., Koolwal, G. B., and Samad, H. A., 2010. *Handbook on impact evaluation: quantitative methods and practices*. World Bank Publications. 31, 32, 39

[60] Lyne, M. C., Jonas, N., and Ortmann, G. F., 2018. “A quantitative assessment of an outsourced agricultural extension service in the Umzimkhulu District of KwaZulu-Natal, South Africa”. *The Journal of Agricultural Education and Extension,* **24**(1), pp. 51–64. 31, 39

[61] Tolk, A., 2013. “Interoperability, composability, and their implications for distributed simulation: Towards mathematical foundations of simulation interoperability”. In Proceedings of the 2013 IEEE/ACM 17th International Symposium on Distributed Simulation and Real Time Applications, IEEE Computer Society, pp. 3–9. 31

[62] Amrose, S., Amrose, S., Kisch, G. T., Kirubi, C., Woo, J., and Gadgil, A., 2008. Development and testing of the berkeley darfur stove. Tech. rep., Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States). 34

[63] Ottosson, H. J. “Analysis of Existing Products Designed for Social Impact With Derived Methods for Handling Social Impact Objectives”. *Manuscript in preparation*. 35

[64] Lofthouse, V., 2014. *Social Issues Cards*. Loughborough University. 35

[65] Zavaleta, D., Samuel, K., and Mills, C., 2014. “Social Isolation: A Conceptual and Measurement Proposal”. *OPHI Working Paper 67*(January), pp. 1–62. 36

[66] Trump, D., 2017. Secure the Border by Deterring and Swiftly Removing Illegal Entrants. Tech. rep., The White House. 40, 41

[67] Owens, B., 2016. “Trump’s border-wall pledge threatens delicate desert ecosystems”. *Nature,* **536**(7616). 41

[68] Roche, D., Mills, D., Gordon, A., Krakoff, S., and Burt, S., 2017. “Environmental Impacts of the Border Wall”. *The Environmental Law Reporter*. 41

[69] Cohn, J. P., 2007. “The environmental impacts of a border fence”. *BioScience,* **57**(1), p. 96. 41

[70] Eriksson, L., and Taylor, M., 2008. “The environmental impacts of the border wall between Texas and Mexico”. *TW Wall, Obstructing Human Rights: The Texas-Mexico Border Wall*, pp. 155–164. 41

[71] Customs and Border Protection, 2017. Federal contract opportunity HSBP1017R0022 for commercial and institutional building construction at Customs and Border Protection Procurement Directorate - IN. Tech. rep., Department of Homeland Security. 41

[72] The White House, 2017. Secure the Border by Deterring and Swiftly Removing Illegal Entrants. 41

[73] The White House, 2018. Remarks by President Trump at Customs and Border Protection Roundtable. 41, 44, 47

[74] Sen, A., 1994. "Human Development Index: Methodology and Measurement.". 49

[75] Kovacevic, M., and Calderon, M. C., 2014. "UNDP's Multidimensional Poverty Index: 2014 Specifications". *Occasional Paper, New York: UNDP Human Development Report Office (Available at http://hdr. undp. org/sites/default/files/specifications_for_c omputation_of_the_mpi. pdf, access date: 2015/02/16)*. 49

[76] U.S. Department of Homeland Security, 2016. Entry/Exit Overstay Report, Fiscal Year 2016. Tech. rep. 50

[77] Sterman, J. D., 2002. "All models are wrong: reflections on becoming a systems scientist". *System Dynamics Review,* **18**(4), pp. 501–531. 52