Toward a Universal Social Impact Metric for Engineered Products That Alleviate Poverty

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One of the purposes of creating products for developing countries is to improve the consumer's quality of life. Currently, there is no standard method for measuring the social impact of these types of products. As a result, engineers have used their own metrics, 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 paper, we introduce a potential universal 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 impacts both anticipated and unanticipated, thereby providing a broader assessment of the product's total impact than with other more specific metrics. The PIM is calculated based on 18 simple field measurements of the consumer. It is inspired by the UN's Multidimensional Poverty Index (UNMPI) created by the United Nations Development Programme (UNDP). The UNMPI measures how level of poverty within a nation changes year after year, and the PIM measures how an individual's poverty level changes after being affected by an engineered product. The PIM can be used to measure social impact (using specific data from products introduced into the market) or predict social impact (using personas that represent real individuals).
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1 Introduction

In 2014, nations around the world collectively provided $161 billion in development aid for developing countries [1]. 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 [2].

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 [3]. As engineers, we tend to prefer data that are 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 [4]. 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 [5]. 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 [6]. 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 [7]. 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 [6–8]. 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 [6]. 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 also simultaneously see a decrease in the prevalence of disease [9]. Likewise, when people gain access to clean cooking and

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heating fuels, they can spend less time collecting firewood while also decreasing their risk respiratory illnesses [10,11]. Additionally, the more education a woman receives, the better off her children will be [12,13]. Contrarily, negative impacts (such as decreasing crop yields) can result when products disregard religious and community rituals [14]. 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" [15]. 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 [16]. 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 [17]. A product's impact and success cannot be determined by its functional capabilities alone (many products with excellent functionality have been abandoned by consumers) [16]. 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 [18]. 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 [19–21]. 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 [22]. 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 [22]. 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.

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 explains the origin of the PIM, Sec. 3 introduces the PIM equations, Sec. 4 introduces important considerations when using the PIM, Sec. 5 using the PIM for determining the impact of motorcycles in a small Brazilian town, and Sec. 6 is the conclusion.

2 The United Nation'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 [23]. 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 not only 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 [24–26]. 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 [27–29].

Some PIM calculation methods are changed from the UNMPI. Most 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.

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.

3.1 Mathematical Relationships.

The equation for the product impact metric

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

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. (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

$$M = \frac{1}{5}(H + E + L + Q + Y) \quad (2)$$

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 [30,31]. 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. (23), and discussed more deeply in Sec. 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 [24,32]. Each dimension is made up of subdimensions, 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 1. Each subdimension follows the form:

$$\check{[\,]} = \begin{cases} \dfrac{\text{Num}}{\text{Den}}, & \text{Num} < \text{Den} \\ 1, & \text{Num} \geq \text{Den} \\ 0, & \text{Num} \leq 0, \text{Den} \leq 0 \end{cases} \quad (3)$$

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

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 body mass index (BMI) ($s_{\text{BMI}v}$), and malnourished BMI ($s_{\text{BMI}a}$), are taken from what U.S. Agency for International Development (USAID) and Centers of Disease Control and Prevention currently use as their standard acceptable values [33,34]. 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 ($h_{k\alpha}$).

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. Finally, all measurements must be scalable from a person who is completely deprived to a person having an acceptable level.

3.2.1 Health. The equation for health is

$$H = \begin{cases} \dfrac{1}{2}(\check{N} + \check{B}), & \text{has children dependents} \\ \check{N}, & \text{has no children dependents} \end{cases} \quad (4)$$

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

$$\check{N} = \frac{s_{\text{BMI}v} - |s_{\text{BMI}v} - s_{\text{BMI}r}| - s_{\text{BMI}a}}{s_{\text{BMI}v} - s_{\text{BMI}a}} \quad (5)$$

Table 1 Standard measurements used in the calculation of the PIM

Standard measurements	Values
Health (H)	
Average good BMI ($s_{\text{BMI}v}$)	21.75[a]
Malnourished BMI ($s_{\text{BMI}a}$)	16[a]
Education (E)	
Acceptable years of schooling ($n_{l\alpha}$)	8[a]
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 h
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

[a]For adults.

where the

$$\check{B} = \frac{n_c - n_{cb}}{n_c} \tag{6}$$

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

$$n_c = n_{cz} + n_{cb} \tag{7}$$

Health includes measurements for the average healthy BMI score ($s_{\mathrm{BMI}v}$), the measured BMI ($s_{\mathrm{BMI}r}$), malnourished BMI score ($s_{\mathrm{BMI}a}$), number of children (n_c), number of child deaths (n_{cb}), and the number of living children (n_{cz}); see Tables 1 and 2 for standard field measurements. A BMI score includes measurements of height (meters) and mass (kilograms). The equation for calculating BMI is $s_{\mathrm{BMI}} = \mathrm{weight}/\mathrm{height}^2$. 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 ($s_{\mathrm{BMI}v}$) and ($s_{\mathrm{BMI}a}$) can be found in growth charts produced by the Centers for Disease Control and Prevention [34]. The healthy BMI score, ($s_{\mathrm{BMI}v}$), is the 50th percentile and the malnourished BMI score, ($s_{\mathrm{BMI}a}$), is the fifth percentile.

3.2.2 Education. The equation for education is

$$E = \begin{cases} \frac{1}{2}\left(\check{S}_c + \check{S}_q\right), & \text{has children} \\ \check{S}_q, & \text{has no children} \end{cases} \tag{8}$$

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

$$\check{S}_c = \frac{n_{cl}}{n_{clg}} \tag{9}$$

Table 2 Field measurements used in the calculation of the PIM

Field measurements
Health (H)
Height
Mass
Measured BMI ($s_{\mathrm{BMI}r}$)
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 ($s_{\mathrm{BMI}r}$)
Multidimensional poverty level (M)
Product impact metric (PIM)

$$\check{S}_q = \frac{n_{ql}}{n_{l\alpha}} \tag{10}$$

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 1 and 2 specify which are standard or field measurements.

3.2.3 Standard of Living. The equation for standard of living is

$$L = \frac{1}{5}\left(\check{F} + \check{T} + \check{W} + \check{E} + \check{I}\right) \tag{11}$$

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

$$\check{F} = \frac{n_{y\alpha}}{n_{y\alpha} + n_{y\beta}} \tag{12}$$

$$\check{T} = \frac{n_{tf}}{n_{tf\alpha}} \tag{13}$$

$$\check{W} = \frac{d_{w\alpha} - d_w}{d_{w\alpha}} \tag{14}$$

$$\check{E} = \frac{h_e}{h_{e\alpha}} \tag{15}$$

$$\check{I} = \frac{\log m_y}{\log m_{yo}} \tag{16}$$

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 1 for details about the standard measurements and Table 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 USAID and other organizations [33]. 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 [33]. 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 known to be contaminated, it is not counted as a water source.

Hours of electricity, h_e in $\check{E}$, are 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 $\breve{I}$, 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 subdimension 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.

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

$$Q = \frac{1}{2}(\breve{R} + \breve{J}) \tag{17}$$

where $\breve{R}$ is the subdimension for hours of employment and $\breve{J}$ is the subdimension for work related injuries. Their equations are

$$\breve{R} = \begin{cases} \dfrac{h_k}{h_{k\alpha}}, & \text{independent or dependent, able} \\ \dfrac{h_{k\alpha} - h_k}{h_{k\alpha}}, & \text{dependent, not able, working} \\ \dfrac{h_{k\iota}}{h_{k\alpha}}, & \text{dependent, not able, not working} \end{cases} \tag{18}$$

$$\breve{J} = \begin{cases} \dfrac{h_k - h_{kj}}{h_k}, & \text{independent or dependent, able} \\ \dfrac{h_k - h_{kj}}{h_k}, & \text{dependent, not able, working} \\ \dfrac{h_{k\iota} - h_{kj\iota}}{h_{ki\iota}}, & \text{dependent, not able, not working} \end{cases} \tag{19}$$

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 1 and 2 for the standard and 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 Eqs. (18) and (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.

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

$$Y = \frac{1}{2}(\breve{P} + \breve{O}) \tag{20}$$

where $\breve{P}$ is the subdimension for protection and $\breve{O}$ is the subdimension for exposure. Their equations are

$$\breve{P} = \frac{n_p}{n_{p\alpha}} \tag{21}$$

$$\breve{O} = \frac{n_{x\alpha} - n_x}{n_{x\alpha}} \tag{22}$$

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 [35–39]. 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. For someone to be a trusted roommate, the consumer must have known them for at least 1 year. Living alone is counted as not living with a trusted roommate. 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.

4 Using the Product Impact Metric

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. One challenge is that it is difficult to make an accurate prediction with limited quantitative data about how products impact users. Clearly, having only limited data will result in larger prediction errors. This is explained in Sec. 5.3. As expected, the figure shows that with more data, more accurate predictions are possible. 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 [40,41].

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 from 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.

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 [42]. The use of personas is further explained in Sec. 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. 1. 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

Fig. 1 Adia buys a bore hole from a team of drillers using the village drill and its impact on her is shown here

4.3 Including a Counterfactual. To attribute an impact to a single product, the impacts of other products, projects, and social influences acting on the consumer cannot be ignored. The sum of these external influences, which also contribute to the social progression of consumers, is called the counterfactual [43]. 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 people's 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

$$PIM_\delta = PIM_\phi - PIM_\tau \tag{23}$$

to determine the true impact (PIM_δ) [44]. 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.

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. 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 [45]. 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 these 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 Sec. 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 [13,46]. Also, women and children are more impacted by products meant to reduce poverty [47]. 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.

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.

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 [43].

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

5.1 Subject and Location Background. The study was conducted in Itacoatiara, Amazonas, Brazil. Itacoatiara has an estimated 99,854 citizens and is on the Amazon River, 169 mi from the state capital, Manaus [48]. 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, see Fig. 2. 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 2947 cars, 10,041 motorcycles, and 7108 mopeds registered [48]. 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 3000 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 do not 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 [49]. 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 [50]. Additionally, from the year 2000 to 2006 for every 1000 motorcycles sold in Brazil, there were 1.24 recorded fatalities and three recorded hospitalizations from motorcycle accidents [50].

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 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 come from The World Bank's databank. Data from this databank were used to create the M_{i-1} point on both Figs. 3 and 4. 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.

Fig. 2 Itacoatiara and its immediate surroundings

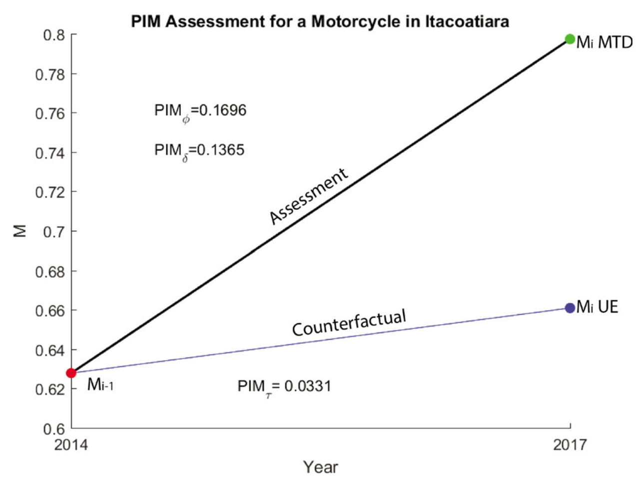

Fig. 3 Assessment of the PIM score of motorcycles on motorcycle taxi drivers

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 is no 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 Fig. 3, point M_i unemployed persons. 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 motorcycle taxi drivers, comes from the motorcycle taxi driver data, specifically, the drivers who have owned their motorcycle for 3 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 Fig. 4. 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 [49–51]. 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 an 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 3 years. All of 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.

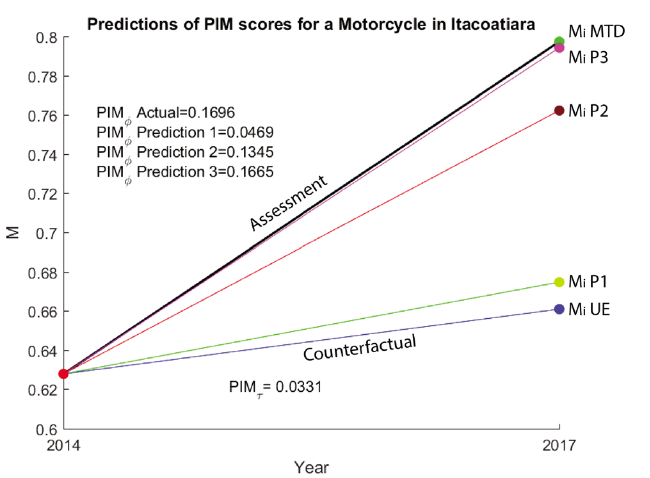

Fig. 4 Product impact metric score predictions of motorcycles on unemployed people who do not own a motorcycle

Counterfactuals were created as described in Sec. 4.3 using data from the World Bank. Personas were created for 5.5th percentile and were tracked for the 3 most recent years, 2013 and 2016. Wherever there was insufficient data for a year, the data were extrapolated from the 2 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 did not 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. For a person to have a score of zero, they must be completely deprived in all of the dimensions. In the course of our study, we did not survey anyone who met this criteria.

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 min 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 are made in this example. This might also give more information on how a product's impact changes over time.

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 [16]. 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 deprived 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.

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

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