Analysis of Perceived Social Impacts of Existing Products Designed for the Developing World, With Implications for New Product Development

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Engineered products often have more social impacts than are realized. A product review was conducted to bring this to light. In this paper, we show the extent to which different social impacts in 11 impact categories are co-present in 150 products and how this can help engineers and others during the product development process. Specifically, we show how social impact categories not previously considered can be identified. The product review resulted in 13,200 data points that were divided into two data sets, one with 8800 data points from which a social impact probability table was created. The remaining data points were then used to validate the table. All data points were then combined to create a final social impact probability table. This table provides insight for how various social impact categories correlate and can assist engineers in expanding their views to include additional social impact objectives and thus achieve a design with broader social impact or a design with minimized unwanted negative social impact. A simple method for predicting social impact is also created in order to assist engineers when developing products with social impacts in mind. [DOI: 10.1115/1.4044323]

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1 Introduction

Most engineers design for the purpose of creating value and improving lives. While so doing, engineers transform and combine raw materials into potentially meaningful products. To be sustainable, different processes are often put in place, aimed at making efficient use of materials, energy, and financial resources. This is referred to as the three pillars of sustainability: environmental, social, and economic sustainability [1–3]. Of these three, the least understood from an engineering design perspective is social sustainability. Social sustainability is defined as positive social impact of a product over time [4]. To better understand a product's social impact over time, we and other researchers have sought to understand how current products impact society [1]. We have done this to inform social impact modeling of new products. In this way, the prediction of social impact is a necessary step toward designing for long-term social impact—or social sustainability.

Tools for assessing the environmental and economic sustainability exist today [5], but the evaluation of social sustainability is seldom discussed in literature [6,7]. This paper suggests that instead of evaluating social sustainability after the fact, a predictive method should be used—just as with economical and environmental sustainability. This would ensure that resources that are being spent on developing products will have a greater potential impact.

To help deepen the understanding of social sustainability, its impact, and how it can be implemented, we have carried out a three-tier approach aimed at a deeper understanding on how engineered products impact society. The first two tiers, a literature review to understand the different areas of social impact [8] and an industry review on practices for how social impact is considered and measured during the product development [9], have already been published by the authors. The third tier is the focus of this paper: what we can learn from the social impacts of existing products, how different social impact categories are correlated, and how we might use that information to anticipate the social impact of new products.

We believe that understanding the social impact of existing products and the extent to which the social impact categories found in literature [8] correlate one with another will allow us to better anticipate the social impacts of a product during the product development process, leading to the creation of products with a greater social impact.

1.1 Evaluating Social Impact.

To be clear, the definition of social impact used in this paper is the impact that engineered products have on the day-to-day lives of persons or communities [10]. The day-to-day impact on people is important since this creates a lasting effect for everyone—a positive improvement in the quality of life of those who come in contact with the products. In our review of industry practice [9], we have found that many engineers lack the tools they need to be able to design for and measure social impact of their products during and after the development process.

1.2 Tier 1: Literature Review.

As a first step to increase the social impact of a product, it is helpful to become familiar with the different types of social impacts that a product can have. To facilitate this, we refer to the study by Rainock et al. [8] where they gathered categories of social impact from both sociology and engineering literature. These categories were identified not only for the purpose of helping to better understand the social impacts of products designed but also for the purpose of discovering and

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Table 1 Social impact categories [8]

Well-being and inequality	Demographics	Interaction and identity
Impact 1. Health and safety Safety and security (real and perceived), activity/exercise, mental and physical health, mortality, improvement of life/health from product	*Impact 5. Education* Education, skills, empowerment	*Impact 9. Conflict and crime* Potential conflicts, crimes, increased or decreased substance abuse, potential of assault
Impact 2. Paid work Earning potential, industrial diversification/change in economic focus	*Impact 6. Family* Alteration in family roles, structure, violence, stressors, ties, and role in society	*Impact 10. Social networks and communication* Impaired or improved personal relations, network's reliance on participation in decision-making process
Impact 3. Stratification Social capital, inequality, introduction of new classes, social status, social mixing	*Impact 7. Gender* Gender roles, violence, stressors, inequality	*Impact 11. Cultural identity/heritage* Weakening/strengthening of values, norms, and beliefs, cultural intolerance, personality traits
Impact 4. Human rights Human rights, respect for indigenous and minority rights, democracy/decision-making participation	*Impact 8. Population change* Transiency of population, age structure, presence of seasonal population	

assessing such impacts. We do not claim that the social impact categories herein to be exhaustive, but use them as a standard found in the literature to compare the 150 products against.

For visual simplicity, we have summarized the data into the form shown in Table 1. This table has three major impact categories, shown as columns, and multiple subcategories shown as rows. Note that there is no implied importance or other meaning to the order of the columns or rows. We have numbered each subcategory to simplify referencing.

To familiarize the readers with these categories and subcategories, the following sections provide brief definitions and further explanations of each category beyond that given in the study by Rainock et al. We do this in order to show how these findings apply to engineering. To clarify them further, we have also included brief examples of actual products from our review of 150 products with names in parenthesis. It is important to note that these examples can also have other social impacts beyond those that are listed here. For example, the GRIT Leveraged Freedom Chair have impacts on health and safety, paid work, stratification, human rights, education, family, and social networks and communication and Contraceptives have impacts on health and safety, stratification, human rights, family, gender, and population change. A brief description and source for each of the 150 products can be found in Table 2.

Impact 1: Health and Safety. Health is said to be "a state of well-being" [67]. This state of well-being can be impacted by the products that an individual is surrounded by. Examples of products that impact health are jaundice treatment lights for newborns (BlueRay Phototherapy), adjustable flues that reduce smoke in biofuel cooking (Cocina Veloz), products enabling family planning (Contraceptives), and products that promotes an active lifestyle (DIY Soccer Ball and the GRIT Leveraged Freedom Chair). Safe housing (UtiYurt), collection device for used needles (Antivirus), and a shield that absorbs shock waves from land-mines (Spider Boot) are examples of products that impact safety.

It is also valuable to consider the ways in which products affect *Health and Safety* even when they are not obviously a health or safety product such as flashlights (BOGO Light) or informational games (Freedom HIV/AIDS) [68,69].

Impact 2: Paid Work. Paid work refers to employment opportunities that can be found within a community that are available to individuals. It also refers to changes in employment rates and economic focus within a company or a product portfolio [68]. While some products can increase the amount of available jobs in a region, other products can simplify work tasks and thus have a negative impact on the amount of jobs in a community and thus impact the local and personal economy [70–72]. Successfully gaining employment often has a great impact on the worker's self-esteem and leads to other positive outcomes such as greater ability to afford food and shelter [73,74].

The following products are examples that can create job opportunities: Vehicles that can be used as taxis or to transport goods (Basic Utility Vehicle), devices that can charge electrical devices (Solar-Rolls), and products that can refine grains and other goods (Burr Mill). Other products, like a wheelchair, can make it possible for a person to get to work (GRIT Leveraged Freedom Chair). These, and products like them, impact employment or can be used to generate income.

Impact 3: Stratification. Stratification refers to social class and the formation of social status [75]. Its purpose is to place people in a social rank according to their contribution to and their worth in society, resulting in inequalities [67,76]. Products that enable education and learning (eGranary Pocket Library), provide Internet in rural areas (AMD Personal Internet Communicator) and enable near-instant translation of languages (Pilot) are examples of products that can enable people to crossover into new stratification layers and give them opportunities that lead to a higher social ranking. Products that enable people to choose when and how to contribute to society will also impact this category (GRIT Leveraged Freedom Chair and Contraceptives).

Impact 4: Human Rights. Human rights "are those liberties, immunities and benefits which, by accepted contemporary values, all human being should be able to claim 'as of right' of the society in which they live" [77]. Since a product can have both a positive and a negative impact on human rights, these rights must be taken into consideration and must be protected and justified by everyone [8]. These rights are the embodiment of the collective conscience of a society [67]. Examples of products impacting this area are those that enable the blind the basic right of reading (Tack-Tiles Braille System), kits for newborns, making sure their inherent right to be safely born and cared for in their first moments of life is fulfilled (Shishu), and shelters for refugees (Global Village Shelter). Other examples are wheelchairs that give back mobility (GRIT Leveraged Freedom Chair) and Contraceptives that provide people greater freedom relative to the complexities of family planning versus health/financial/career planning.

Impact 5: Education. Education is the opportunity to learn or the process for gaining new knowledge and capabilities. It can be

Table 2 Products Included in the Analysis

Product name	Product description	Source
Adaptive Eyecare	Corrective eyeglasses with adjustable prescription	[11]
Afridev pump	Lever action handpump for water	[13]
Air X (wind turbine)	Efficient small wind turbine for low energy needs	[11]
Air2Water Dolphin 2/Dragonfly M18 (atmospheric water generator)	Atmospheric water generator that collects and purifies water from the surrounding air	[11]
Alcohol Stove	Alcohol stove made with locally sources materials	[11]
Alive and Kicking (soccer ball)	Soccer ball with educational messages printed on the ball for developing countries	[11]
AMD Personal Internet Communicator	Device to allow people in less developed countries access to internet	[20]
Antivirus (needle canister)	Cap that turns a regular soda can into a safe needle disposal	[11]
Aquacube Containerized Water Treatment Plants	Mobile water-treatment plant, all in a shipping container	[11]
Aquaduct (water filtration)	Bicycle that stores and filter water during transport	[11]
AquaPak	Portable bag for pasteurization of water by the use of sunlight	[11]
Aquastar Flow Through	System that treats water in large batches, enough to generate income	[20]
Aquastar Plus!	Portable UV water treatment system in a bottle	[20]
Bamboo Treadle Pump	Affordable water pump for irrigation	[20]
Basic Utility Vehicle (BUV)	Economic vehicle to transport goods and people	[11]
BCK Solar Cooker	Solar powered food cooker	[11]
Berkeley Darfur Stove	Fuel-efficient stove with low emissions	[28]
Better Shelter	Innovative housing solutions for displaced people	[31]
Big Boda Load-carrying Bicycle	Affordable bike built for carrying heavy loads	[20]
BioLite HomeStove	Clean burning stove with the ability to charge USB powered devices	[34]
BioSand Water Filter	Household water filter	[36]
BlueRay Phototherapy	Affordable infant phototherapy device with long-lasting LED lights	[11]
BOGO Light	Long lasting solar LED flashlight	[11]
BRCK	Durable mobile WiFi hotspot, providing internet in rural areas	[40]
Burr Mill	Economic and reliable crop mill	[11]
Calfee Bamboo Bike	Bike with frame made of bamboo	[11]
Clay Water Filters	DIY clay water filter	[11]
Cocina Veloz (pot skirts)	Pot skirts that improve most stoves thermal efficiency and reduces required fuel	[43]
Community Cooker (kitchen)	Communal cooker/oven that uses trash for fuel	[44]
Contraceptives	Device or drug that prevents pregnancy	[46]
Cyclean (washing machine)	Pedal-powered washing machine	[11]
D.Light A1 Solar Lantern	Affordable, portable solar lantern	[47]
Daily Dump (compost system)	Pot compost system	[11]
Day Labor Station	Employment hiring center	[20]
DFA POC Diagnostics: Immunity	Low-cost diagnostic tool to test for successful vaccination against tetanus and measles	[48]
DFA POC Diagnostics: Liver Function	Low-cost liver function test	[49]
DFA POC Diagnostics: Nucleic Acid Detection	Device for early diagnosis of HIV in infants	[50]
DFA POC Diagnostics: Small Farmer Support	Heat test for cows for minimally-trained technicians	[51]
DIY Biodiesel and Strait Vegetable Oil (SVO) Fuel	Eco friendly biodiesel	[11]
DIY Soccer Ball	Stitched soccer ball casings sold by AIDS victims	[11]
DREV Low-cost Microscope	Low-cost microscope	[55]
DREV ReMotion Knee	Affordable high-performance knee joint for amputees	[57]
DTM Firefly Phototherapy	Jaundice treatment in newborns	[59]
DTM NeoNurture Newborn Incubator	Low-cost newborn incubator	[59]
DTM Otter Newborn Warmer	Affordable solution to prevent hypothermia for premature newborns	[59]
DTM Pelican Pulse Oximeter	Portable pulse oximeter to diagnose pneumonia in newborns	[59]
Ecocina Cookstove	Mini Ecosystem that uses fauna and bacteria to treat water and sewage	[61]
Eco-Machines (mini ecosystem)	Cookstove that reduces fuel consumption and pollutants	[11]
eGranary Pocket Library	Database with educational materials stored on a microchip	[63]
Envirolet FlushSmart VF	Low-flush, vacuum toilet that composts the waste	[11]
EyeNetra NETRA Autorefractor	Smartphone powered mobile eye diagnostic and vision screening	[12]
EyeNetra Netrometer Lensometer	Smartphone-based netrometer	[14]
EyeNetra Netropter Handheld Phoropter	Affordable and portable phoropter	[16]
FairWater BluePump	Handpump for water wells	[17]
Freedom HIV/AIDS (game)	Game to increase awareness for HIV/AIDS	[11]
Freeplay Encore Radio	Rechargeable world radio with ability to charge USB devices	[19]
GCS Bicycle Phone Charger	Phone charger integrated on a bicycle	[21]
GE Vscan Portable Ultrasound	Portable ultrasound device	[23]
Global Village Shelter (housing)	Low cost emergency shelters	[20]
Grameen Danone	Affordable yogurt that compensates for nutritional deficiencies	[11]
Green Cell (battery dispenser system)	Universal battery dispenser system	[11]
GreenFire Technology Stoves	Economic, fuel-efficient cookstove	[11]
GRIT Leveraged Freedom Chair	Wheelchair for use in rough terrain	[26]
GROW	Hybrid device to collect solar and wind power	[11]
Hippo Roller	Economic water transportation	[11]
HYmini	Solar or wind powered charger	[11]
iDE Ceramic Water Filter	Simple filter for cleaning water	[29]
iDE Drip Irrigation	Economic irrigation system	[20]

Table 2 *Continued*

Product name	Product description	Source
iDE Multiple Use Water Storage Systems	Water resource management that taps and stores water for households and small communities	[32]
iDE Rope Pump	Low-cost handpump	[32]
iDE Sprinkler Irrigation	Efficient irrigation system	[32]
iDE Treadle Pump	Human-powered suction pump for irrigation	[32]
iDE Water Storage Systems	Stores water captured in monsoon rains for use during dry season	[20]
IKEA SUNNAN Solar Lamp	Solar powered lamp for off the grid households	[41]
Inclusive Edge Canopy	Canopy providing a gathering place	[20]
India Mark II/III pump	Lever action handpump for water	[42]
IntelMobile Clinical Assistant	Assists healthcare professionals by compiling medical information	[11]
Internet Village Motoman	Internet for rural villages	[20]
Jaipur Foot Prosthetic	Low-cost foot prosthetic	[11]
Janani	Postpartum care kit for women	[35]
Janma	Clean birth kits sold in a stylish purse	[35]
Kanya	Menstrual hygiene kit	[35]
Kenya Ceramic Jiko	Fuel efficient charcoal stove	[20]
KickStart Domed Pit Latrine Slab Kit	Slab to seal off human waste in refugee camps	[20]
KickStart Moneymaker Block Press	Block press for making durable bricks	[20]
KickStart Moneymaker Hip Pump	Lightweight pressure irrigation pump	[20]
KickStart Super Moneymaker Treadle Pump	Manual treadle irrigation pump	[20]
Kiln	Small natural gas kiln to fire pottery	[52]
Kinkajou Microfilm Projector and Portable Library	Low-cost literacy library with solar-powered projector	[11]
Lampen	Self electrifying pen that provides light	[53]
Laveo	Portable, self-contained toilet that requires no water	[56]
Learning Landscape (playground)	Playground that teaches math through games	[11]
LIFESAVER Bottle	Bottle with built in water filtration cartridge	[11]
LifeStraw	Water filter for individual use	[11]
LifeStraw Family	High-capacity water purifier for families	[11]
Low-cost Water Testing	Economical water testing	[11]
M2E Technology	Battery charger powered by kinetic energy	[11]
Mad Housers Hut (housing)	Secure temporary shelters for displaced people	[20]
MakaPads	Cheap disposable sanitary pads for women	[64]
Maya Pedal	Repurposes bicycles to create pedal-powered machines	[11]
Mechanical Advantage Tourniquet	Self administered tourniquet to stop bleeding	[11]
Menstrual Cups	Washable silicon cup to collect menstrual fluids	[15]
MIT Lab Sugarcane Charcoal Press	Creates fuel from sugarcane waste	[11]
Montessori Toys	Toys to facilitate learning through exploration	[11]
Nokia 1100 (mobile phone)	Low-cost and reliable mobile phone	[18]
One Laptop Per Child	Laptop for the developing world	[11]
OneDollarGlasses	Frames made locally by hand with supplied lenses	[22]
PermaNet	Long-lasting insecticidal net for malaria prevention	[24]
Pilot (translation device)	Earphones that translates languages in real time	[25]
Plumpy)nut	Food bar with high nutritional value	[11]
Portable Light Project	Local handcraft with solar panel and LED lights and batteries	[20]
Pot-in-Pot Cooler	Simple refrigeration system to preserve crop	[20]
Q Drum	Economic water transportation	[20]
Rainwater Catchment Systems	System to catch potable rain water	[11]
Rapid Deployable System (RDS)	Durable and portable shelter	[11]
ReadyPay	Pay-as-you-go solar charger	[27]
Roundabout PlayPump	Pumps water from well into a tank by having children play on a merry-go-round	[30]
ROVAI Rope Pump	Water pump for the developing world	[11]
SAFE AGUA Water System	System for distributing water inside a household	[33]
Shishu	Essential kit for newborns	[35]
Single Cell Battery Charger for Portable Electronic Devices	Replaces disposable batteries with rechargeable batteries	[37]
Small-scale Photovoltaic-powered Reverse Osmosis (PVRO) Desalination Plants	Produces potable water for remote locations	[38]
sOccket	Soccer ball that generates electricity	[39]
SODIS	DIY technique to disinfect water with the help of the sun	[11]
Solar Aid (hearing aid)	Solar-powered hearing aid charger	[20]
Solar Dish Kitchen	Communal solar-powered kitchen	[20]
Solar Home Lighting System	Wireless solar-power lighting	[20]
SolarRolls	Solar panel charger	[11]
Solidarites International Garden-in-a-Sack	Grow produce in a sack	[45]
Solio Classic Universal Hybrid Charger	Device to charge electronics using the sun	[11]
Spark (computer)	Mobile learning tool for children worldwide	[11]
Spider Boot	Boot platform with deflector-shell that absorbs shock waves of land-mines	[11]
Starsight Project	Reliable solar lighting to keep public areas lit and to provide internet	[11]
Subtle Safety Ring	Ring with sharp point to be used in self defense	[11]
Sudanese Refugee Cookware	Easy to transport cookware for refugees	[11]
Sugarcane Charcoal	Wood and smoke free cooking fuel	[11]
Tack-Tiles Braille System	Interactive braille block learning system	[11]
Tessera (game)	Interactive educational game for refugees	[11]

Table 2 *Continued*

Product name	Product description	Source
UGASTOVE	Stove project that empowers women and creates income generating business opportunities	[11]
UtiYurt (housing)	Economic and durable shelter	[54]
Vaccine Patch - Transcutaneous Immunization	Needle-free alternative for immunization	[11]
Village Drill	Durable, simple, and affordable hand-powered bore-hole drill	[58]
Weza Portable Energy Source	Foot powered device to generate energy	[11]
Whirlwind RoughRider	Rugged, affordable wheelchair	[11]
Windbelt	Utilizes vibrations to generate energy	[11]
World Cart	Cheap transportation solution for developing countries	[60]
Worldbike Prototype	High capacity bike	[20]
Zambulance	Stretcher on two wheels that can connect to a bicycle or motorcycle	[62]
ZeroFly Screen	Screen with incorporated insecticide for livestock	[65]
ZeroFly Storage Bag	Food grade storage bag with incorporated insecticide	[66]

acquired formally or informally [68,69]. Access to education has almost universally great social impact and improves the lives of those involved [78,79]. It can also empower the students by changing their engagement in the community [68]. Products that give light in the home (The Solar Home Lighting System), those that can provide information and curriculum to students (One Laptop Per Child), those that give close access to water, eliminating time spent carrying water far distances (Village Drill, providing access to groundwater), and that enable students to go to school (GRIT Leveraged Freedom Chair) creates impact in this area.

Impact 6: Family. Family is a close domestic group bounded by blood or legal ties. This union is traditionally for raising children and supporting each others' survival [75,80]. Products can create stronger bonds within the family unit, reduce the quality family time, and also cause a change in how each member perceives their individual role by changing how routine tasks are performed [8]. Products providing basic needs such as cooking (Ecocina Cookstove), maximizing the use of family resources by preventing food from spoiling (Pot-in-Pot Cooler), enable family planning (Contraceptives), and help facilitate family members to carry out their roles (GRIT Leveraged Freedom Chair) are examples of products that have impact on the family.

Impact 7: Gender. Gender refers to the social and cultural norms associated with identifying as masculine or feminine as well as the social roles enacted by men and women. Although products typically do not affect one's gender identity directly, a product can impact or reinforce gender roles, gender inequality, and gender-based violence [75]. These impacts can be manifest within a family, the workplace, or other social settings [81,82]. Self-defense products (Subtle Safety Ring), postpartum kits (Janani), and birth control products (Contraceptives), all of which can empower women, are examples of products that have impact in this area.

Impact 8: Population Change. Population change is a measure that accounts for the deaths, births, and the move-ins/move-outs of a population [67]. Population change can be linked to products [72]. One example is a product that influences a population in such a way that it causes move-ins/move-outs of the population [72]—such as irrigation (iDE Sprinkler Irrigation) or a sanitation system (Daily Dump) being added to a community, thus increasing the desirability of that community. Another class of products that impacts this area is shelter (A Better Shelter). Finally, products that help manage family size will also impact this category (Contraceptives).

Impact 9: Conflict and Crime. Conflicts are activities that go against the social establishment. The impacts can be both positive and negative. On the one hand, conflict can strengthen a group's purpose and identity. But, on the other hand, conflict can cause groups to fracture and break up [67]. Crime is defined as a violation of set laws [75]. Conflicts are usually punished by the social network, while crimes are punished by set laws [67]. Products can be used not only to reduce the probability of crime but also to perpetrate a crime. An example of a product that can reduce the probability of crime is the street light (Starsight Project). Mobile phones can be used when perpetrating drug and gang crimes (Nokia 1100). Temporary housing for refugees (Rapid Deployable System) can ease the negative impact of conflict.

Impact 10: Social Networks and Communication. A social network is "a finite set of actors and the relation or relations defined on them" [83]. Social networks can be divided into three units: micro level (small groups), meso level (organizations or fields), and macro level (cities or nations). These levels can have no connections, weak connections, or strong connections between them [67]. Product impacts can make network connections within a level stronger or weaker, even to the point of dissolving them [78,82,84]. Bicycles (Calfee Bamboo Bike), wheelchairs (GRIT Leveraged Freedom Chair), and other vehicles that create mobility impact the size of networks and lead to an increase of interactions between people.

Communication is the "process by which messages are transferred from a source to a receiver" [85]. It is found in every social situation and can be broken up into five different types of communication: conversation with self, face-to-face interactions, group communication, mass communication, and nonhuman communication (communication with machines and computers). The type of communication that is carried out and the effectiveness of it can impact social systems because of how a message can be interpreted or understood [75]. Clearly, products can change how communication is done [82]. Mobile phones (Nokia 1100), Wi-Fi hotspots (Internet Village Motoman), and translation devices (Pilot) are some examples of products in this area.

Impact 11: Cultural Identity/Heritage. "Cultural heritage is an expression of the ways of living, developed by a community and passed on from generation to generation, including customs, practices, places, objects, artistic expressions and values" [86]. Products can influence the ways that cultural heritage is passed on from generation to generation and thus change the identity and heritage of a culture over time [69,84,87]. Products that can utilize local skill sets and crafts (The Portable Light Project) and provide enlightenment on cultural behavior and stigmas by showing correlation between HIV in infants and cultural practices [88] (DFA POC Diagnostics: Nucleic Acid Detection) are examples that impact cultural identity and heritage.

1.3 Tier 2: Industry Review. In the industry review conducted by Pack et al. [9], the 11 social impact categories introduced in Ref. [8] and discussed in the previous section were used to

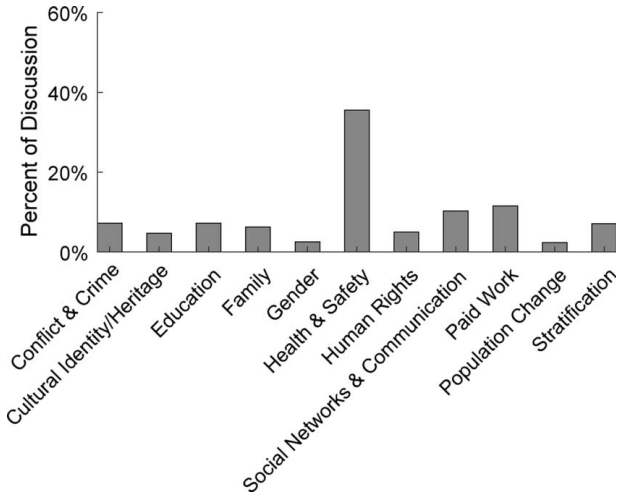

Fig. 1 Percent of social impact considerations in each social impact category [9]

understand to what extent these impacts were being considered by professional engineers in industry. Interviews were conducted with 46 industry professionals to glean insights regarding processes, metrics, and general perspectives relating to the social impact categories. In the study, it was found that not all impact categories are considered equally when designing a product (see Fig. 1). In addition, it was found that very few processes exist to predict and quantify the social impact of a product.

Pack et al. conclude from the industry review that engineers lack sufficient tools to assist them in their work to consider social impact holistically and that they rely heavily on intuition to inform many of their product decisions that affect the social impact [9].

1.4 Tier 3: Product Review. Recall that the purpose of this and the other two papers [8,9] in this three-tier approach is to help deepen the understanding of what social impact is and how engineered products impact society. With this, we hope to shift engineering decisions relative to social impacts from being intuition based to instead being information based. To assist with this, we conducted a review of 150 existing products to find the extent to which the social impact categories discussed in Sec. 1.2 appear together in engineered products. As will be shown, this review lays the foundation for predicting social impacts of products.

The next section will discuss the research approach, followed by a results section. These results will then be discussed and a method for predicting social impact will be presented.

2 Research Approach

The product review was carried out by a multidisciplinary team that choose a set of products to be included in the product review, and they then evaluated each product related to social impact categories found in Sec. 1.2. The correlation between the different social impact categories was then discovered, and a probability chart was developed. Below is an overview of how the product review was carried out:

(1) Choose team (Sec. 2.1),
(2) Select criteria for including products (Sec. 2.2),
(3) Create product review instrument (Sec. 2.3),
(4) Distribute instrument (Sec. 2.3),
(5) Evaluate instrument data (Sec. 2.4), and
(6) Evaluate the results (Sec. 3).

The results from the product review, the correlation of social categories, and a social impact probability table can be found in Sec. 3.

2.1 Research Team. Being cognizant that we cannot fully eliminate research bias, the product review and evaluation were carried out by a team of people from both sociology and engineering disciplines. The team consisted of three females and one male social scientists, and two female and two male engineers. Age, home country, and educational level were also considered when choosing the respondents. Three were aged above 35 years, two grew up and received university degrees outside the United States (Europe and Asia), and three had graduate degrees. (See Sec. 3.1 for the intraclass correlation coefficient (ICC) for the respondents.)

2.2 Selection Criteria for Products. The following questions were used as selection criteria for the products that were included in the review. Products for which "yes" was the answer for all questions were included.

(1) Is the product designed specifically for social impact?
(2) Can we learn something about social impact from this product?
(3) Does the product have the potential to better the life of a person using it?

The products included in the analysis were selected from our own findings, conference proceedings by Troxell and Kim [89], and from two books, one by Pilloton [11] and the other by Smith [20].

One hundred fifty products were chosen to be included in the product review. The names, descriptions, and sources of these products can be found in Table 2. While many of these products were designed for the developing world, the findings in this paper may also benefit any product that is designed with a specific social impact in mind, regardless of its intended market. For example, while the GRIT Leveraged Freedom Chair is designed for a foreign market and has impacts in categories 1, 2, 3, 4, 5, 6, and 10, the GRIT Freedom Chair is its domestic counterpart that also has social impacts, but in slightly different categories: impacts 1, 3, 4, and 5. From this, we observe that products can be designed for social impact regardless of whether it targets the developing world, the developed world, or both simultaneously. We acknowledge that the review of products in this paper is not exhaustive. We also acknowledge that the impact assessed is "perceived impact," and in light of this, we chose the best set of respondents we could.

2.3 Product Review and Distribution. To extract the social impacts of products, a review instrument was created to collect and compare the social impacts as perceived by both social scientists and engineers. We know that the best impact to measure is real-life impact. However, this is not easily done since we are looking at long-term, comprehensive impact, and the actual impact can only be known with the data spanning over a large extended period of time (potentially decades). This is why we chose to extract *perceived* impact. This choice is supported by Expert Systems where a knowledge-base is used to make informed decisions [90,91].

A Qualtrics online survey platform was used to create the review instrument [92]. The review consisted of 1650 questions where 150 products were evaluated relative to each of the 11 social impact categories. Each of the eight respondents evaluated all 1650 questions resulting in 13,200 data points. For each product, the respondent ranked the 11 social impact categories on a Likert scale[2] from *Fundamentally Related* to *Not Related* for the product under evaluation (see Fig. 2).

To further minimize reviewer bias, the survey platform randomized the order the social impact categories were displayed each time a new product was introduced. The order of the products was also randomized for each respondent. Due to the high number of questions in the survey, the respondents were able to

[2]"A scaled response continuum measured from extreme positive to extreme negative (or vice versa) in five, seven, or nine categories" [93].

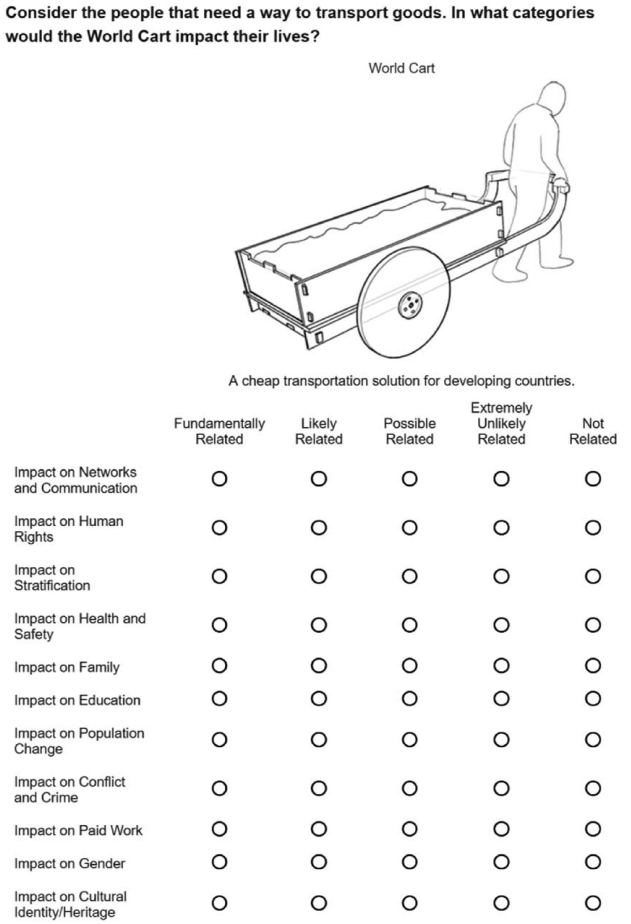

Fig. 2 Example of one question set in the product review instrument

pause and resume the survey to prevent respondent burnout. This resulted in an total average working time of approximately 3 h answering survey questions, spread out over a longer period of time ranging from half a day to several days.

The product review was distributed to the research team discussed earlier in Sec. 2.1. Before starting the review, the respondents were asked to read an instruction sheet and familiarize themselves with the impact categories. The instruction sheet also showed how the review instrument was laid out.

2.4 Evaluation of Instrument Data. Statistical tools were used to evaluate the review data and to ensure that it had statistical significance and that there was agreement among the respondents (see Sec. 3.1). The experimental probabilities (based on observations) were then calculated for each social impact category. The co-presence of impacts in two categories were also calculated. Equations (1) and (2) are for general probabilities, Eq. (3) is for joint probabilities, and Eqs. (4)–(6) are for calculating conditional probabilities (both experimental and theoretical probabilities are calculated the same way) [94–96]. All analyses were done considering dependent events.

General probabilities:

$$P(A) = \frac{n_A}{n} \tag{1}$$

$$P(B) = \frac{n_B}{n} \tag{2}$$

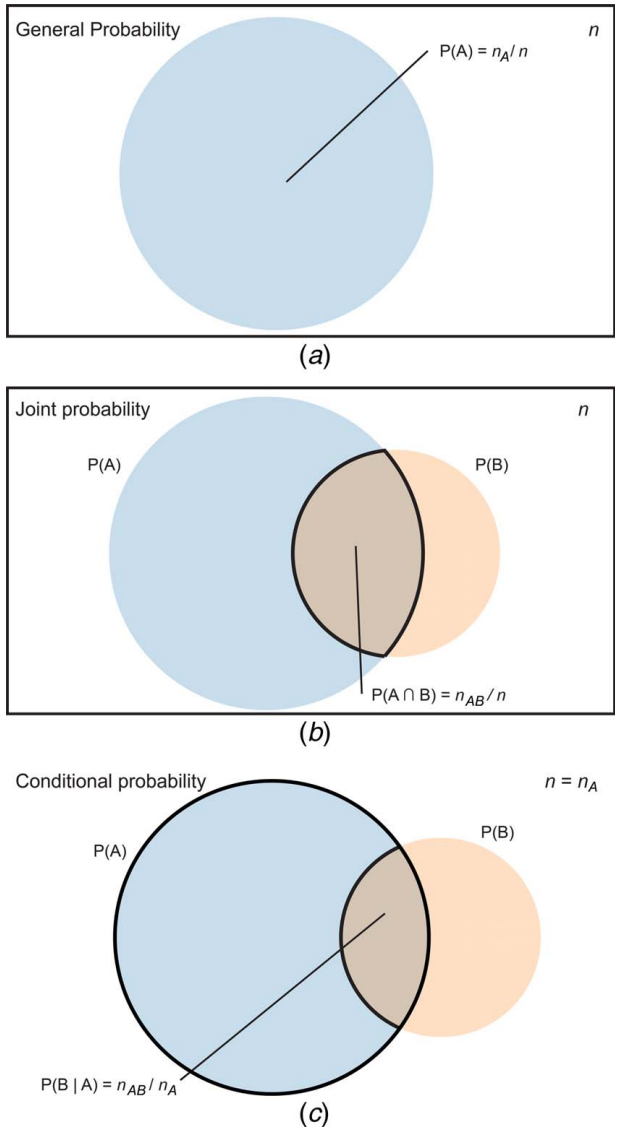

Fig. 3 Venn diagrams showing (*a*) general probability for an event, (*b*) joint probability for two events, (c) conditional probability for two events

Joint probabilities:

$$P(A \cap B) = \frac{n_{AB}}{n} \tag{3}$$

Conditional probabilities:

$$P(A|A) = \frac{n_A}{n_A} = 1 \tag{4}$$

$$P(B|A) = \frac{P(A \cap B)}{P(A)} = \frac{n_{AB}}{n_A} \tag{5}$$

Chain rule of conditional probabilities:

$$P(C_1 \cap \ldots \cap C_k) = P(C_1)P(C_2|C_1) \ \ldots \ P(C_k|C_1 \cap \ldots \cap C_{k-1}) \tag{6}$$

where A, B, and C_i are different events; n_A is the occurrence of event A; n_B is the occurrence of event B; n_{AB} is the occurrence of events A and B; and n is the number of total sample.

Figure 3(*a*) shows the general probability for an event, Fig. 3(*b*) shows the joint probability for two events, and Fig. 3(*c*) shows the conditional probability for two events.

3 Results

The product review produced a total of 13,200 data points from eight respondents. SPSS [97] was used to analyze the consistency of the review responses.

After the agreement of the respondents was analyzed, the data set was separated into two sets in order to use one for validation. The probability of social impacts being associated with the product set was calculated using Eqs. (1)–(3), creating Table 3. This table was then validated with the second data set (see Tables 4 and 5). After the validation, the two data sets were combined to create a probability table that can be used for future design work (see Table 6). Equations (4) and (5) were then used to calculate the conditional probability, capturing the condition when one impact is known to exist and the designer wants to know the probability of other impacts existing concurrently (see rows in Table 7).

3.1 Respondent Agreement Analysis. The agreement analysis was carried out using SPSS. The ICC was calculated in a mixed mode to find the agreement between the respondents [98,99]. The ICC was found to be 0.855 with a significance value of 0.00, indicating that there was a good level of agreement between the respondents [100]. See Table 8 for the ICC results and Table 9 for the commonly accepted ICC reliability levels [98]. Because of the good level of agreement between the respondents, we are confident that the expert respondents reviewed the 150 products in such a way that statistically reliable data were produced.

3.2 Probability Samples. Of the sample of 150 products, 100 products were selected as one data set. It was done randomly to "ensure constant and independent probabilities" [101]. The remaining 50 products were put into a separate data set to be used to validate the first set [93].

Figure 4 shows the impact between two categories. In order for a correlation between two impact categories to be considered related, the responses must be either Fundamentally Related or Likely Related as shown in the box in Fig. 4. It can also be seen in the figure that the majority of the responses for *Health and Safety* are *Fundamentally Related*, while for *Population Change*, the majority of the responses are *Not Related*.

The remaining correlations can be found in Fig. 5 where trends can be found in a similar fashion. Most clearly, the category of *Health and Safety* has the majority of the responses in the row/column for *Fundamentally Related*, while the category of *Conflict and Crime* has a majority of responses in the row/column for *Not Related*.

3.3 Probability Table and Prediction. The data set with 100 products was then analyzed using MATLAB and STATA [102] to learn how the different social impact categories correlate. The

Table 3 General probability (shaded cells) and joint probability (nonshaded cells) when there is no known impact, observed from 100 randomly selected products

	Health and safety	Paid work	Stratification	Human rights	Education	Family	Gender	Population change	Conflict and crime	Social networks and communication	Cultural identity/ heritage
Health and safety	**0.746**	0.318	0.046	0.213	0.121	0.144	0.138	0.080	0.095	0.190	0.116
Paid work	0.318	**0.368**	0.028	0.119	0.064	0.109	0.081	0.054	0.056	0.173	0.093
Stratification	0.046	0.028	**0.055**	0.023	0.020	0.018	0.014	0.019	0.019	0.024	0.018
Human rights	0.213	0.119	0.023	**0.329**	0.105	0.045	0.044	0.044	0.091	0.053	0.091
Education	0.121	0.064	0.020	0.105	**0.189**	0.020	0.019	0.034	0.065	0.038	0.049
Family	0.144	0.109	0.018	0.045	0.020	**0.159**	0.034	0.029	0.016	0.066	0.034
Gender	0.138	0.081	0.014	0.044	0.019	0.034	**0.153**	0.016	0.013	0.048	0.033
Population change	0.080	0.054	0.019	0.044	0.034	0.029	0.016	**0.096**	0.044	0.024	0.031
Conflict and crime	0.095	0.056	0.019	0.091	0.065	0.016	0.013	0.044	**0.156**	0.023	0.043
Social networks and communication	0.190	0.173	0.024	0.053	0.038	0.066	0.048	0.024	0.023	**0.209**	0.053
Cultural identity/ heritage	0.116	0.093	0.018	0.091	0.049	0.034	0.033	0.031	0.043	0.053	**0.155**

Table 4 Showing the number of predictions for each social impact category (out of 50 products) using the probabilities in Table 3

	Health and safety	Paid work	Stratification	Human rights	Education	Family	Gender	Population change	Conflict and crime	Social networks and communication	Cultural identity/ Heritage
Health and safety	37	16	2	11	6	7	7	4	5	10	6
Paid work	16	18	1	6	3	5	4	3	3	9	5
Stratification	2	1	3	1	1	1	1	1	1	1	1
Human rights	11	6	1	16	5	2	2	2	5	3	5
Education	6	3	1	5	9	1	1	2	3	2	2
Family	7	5	1	2	1	8	2	1	1	3	2
Gender	7	4	1	2	1	2	8	1	1	2	2
Population change	4	3	1	2	2	1	1	5	2	1	2
Conflict and crime	5	3	1	5	3	1	1	2	8	1	2
Social networks and communication	10	9	1	3	2	3	2	1	1	10	3
Cultural identity/ heritage	6	5	1	5	2	2	2	2	2	3	8

Table 5 Showing the number of observations for each social impact category out of the remaining 50 observed products

	Health and safety	Paid work	Stratification	Human rights	Education	Family	Gender	Population change	Conflict and crime	Social networks and communication	Cultural identity/ heritage
Health and safety	36	15	3	11	8	6	5	4	5	10	7
Paid work	15	18	1	7	5	5	4	4	3	8	6
Stratification	3	1	3	1	1	1	1	1	1	1	1
Human rights	11	7	1	18	8	2	2	2	6	4	7
Education	8	5	1	8	15	1	2	3	5	4	5
Family	6	5	1	2	1	7	1	1	1	3	2
Gender	5	4	1	2	2	1	7	1	0	2	1
Population change	4	4	1	2	3	1	1	4	1	2	3
Conflict and crime	5	3	1	6	5	1	0	1	9	2	4
Social networks and communication	10	8	1	4	4	3	2	2	2	12	4
Cultural identity/ heritage	7	6	1	7	5	2	1	3	4	4	11

Table 6 Observed probability (shaded cells) and observed joint probability (nonshaded cells) for when there is no known impact, observed from all 150 products

	Health and safety	Paid work	Stratification	Human rights	Education	Family	Gender	Population change	Conflict and crime	Social networks and communication	Cultural identity/ heritage
Health and safety	**0.735**	0.314	0.048	0.215	0.134	0.136	0.128	0.077	0.093	0.190	0.124
Paid work	0.314	**0.363**	0.028	0.123	0.077	0.106	0.078	0.062	0.056	0.171	0.101
Stratification	0.048	0.028	**0.058**	0.022	0.023	0.015	0.015	0.018	0.018	0.024	0.019
Human rights	0.215	0.123	0.022	**0.342**	0.123	0.043	0.045	0.044	0.098	0.058	0.107
Education	0.134	0.077	0.023	0.123	**0.227**	0.018	0.023	0.042	0.079	0.053	0.068
Family	0.136	0.106	0.015	0.043	0.018	**0.149**	0.030	0.028	0.018	0.065	0.033
Gender	0.128	0.078	0.015	0.045	0.023	0.030	**0.147**	0.015	0.011	0.044	0.030
Population change	0.077	0.062	0.018	0.044	0.042	0.028	0.015	**0.093**	0.038	0.029	0.038
Conflict and crime	0.093	0.056	0.018	0.098	0.079	0.018	0.011	0.038	**0.167**	0.029	0.053
Social networks and communication	0.190	0.171	0.024	0.058	0.053	0.065	0.044	0.029	0.029	**0.218**	0.059
Cultural identity/ heritage	0.124	0.101	0.019	0.107	0.068	0.033	0.030	0.038	0.053	0.059	**0.177**

Table 7 Observed conditional probability of impact when one category is known

	Health and safety	Paid work	Stratification	Human rights	Education	Family	Gender	Population change	Conflict and crime	Social networks and communication	Cultural identity/ heritage
Health and safety	**1**	0.427	0.066	0.293	0.183	0.185	0.173	0.104	0.127	0.259	0.169
Paid work	0.867	**1**	0.076	0.340	0.211	0.292	0.214	0.170	0.154	0.471	0.278
Stratification	0.841	0.478	**1**	0.377	0.391	0.261	0.261	0.319	0.304	0.420	0.333
Human rights	0.629	0.361	0.063	**1**	0.361	0.124	0.132	0.129	0.285	0.171	0.312
Education	0.592	0.338	0.099	0.544	1.000	0.081	0.099	0.184	0.349	0.232	0.301
Family	0.911	0.709	0.101	0.285	0.123	**1**	0.201	0.184	0.117	0.436	0.223
Gender	0.869	0.528	0.102	0.307	0.153	0.205	**1**	0.102	0.074	0.301	0.205
Population change	0.829	0.667	0.198	0.477	0.450	0.297	0.162	**1**	0.414	0.315	0.414
Conflict and crime	0.560	0.335	0.105	0.585	0.475	0.105	0.065	0.230	**1**	0.175	0.320
Social networks and communication	0.870	0.782	0.111	0.267	0.240	0.298	0.202	0.134	0.134	**1**	0.271
Cultural identity/ heritage	0.703	0.571	0.108	0.604	0.387	0.189	0.170	0.217	0.302	0.335	**1**

respondents' answers were calculated into probabilities and put into Table 3 where the shaded cells are for the general probability for one impact to occur (using Eqs. (1) and (2)), and the nonshaded cells show joint probability for two impacts occurring (using Eq. (3)).

This table was then used to predict social impact for 50 random products (products that would fulfill the requirements for product selection found in Sec. 2.2). This prediction can be seen in Table 4.

3.4 Validation of Probability Table. The remaining 50 products were then evaluated and the observed impact for all categories together with their joint impacts were counted and put into Table 5.

Table 8 Intraclass correlation coefficient

	Intraclass correlation	95% Confidence interval		F test significance
		Lower bound	Upper bound	
Average measures	0.855	0.831	0.875	0.00

Table 9 Intraclass correlation coefficient reliability chart [98]

ICC value	Reliability
0–0.5	Poor
0.5–0.75	Moderate
0.75–0.9	Good
0.9–1	Excellent

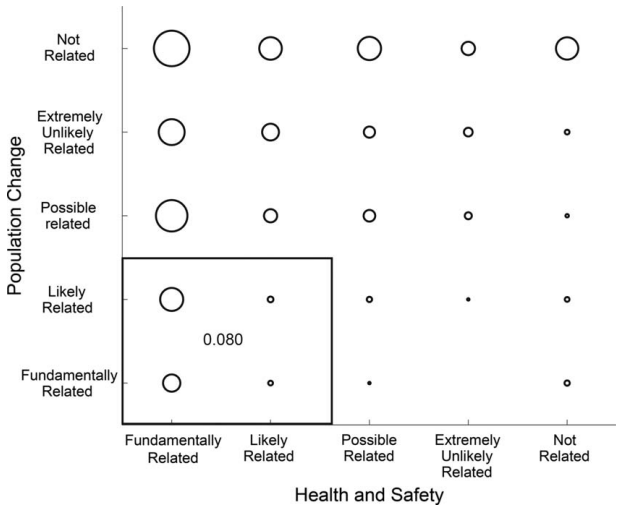

Fig. 4 Scatterplot showing the correlation between *Health and Safety* and *Population Change* where the size of the circles indicates the number of times the respondents gave the particular rating. The value of the probability for *Fundamentally* and *Likely Related* is also shown (see box in lower left corner of figure). The data from the 100 randomly selected.

This was done in order to validate the probability table created earlier (Table 3).

An analysis for statistical significance of the predicted and observed values for 50 products (found in Tables 4 and 5) was carried out in MATLAB. The coefficient came to 0.9683 with a significance value of 0.00, indicating that there is a strong relationship between the two tables and we therefore draw the conclusion that the values did not happen by chance, the data are statistically significant, and the probability table is validated (Table 3).

3.5 Final Probability Table. After the validation of the probability table, the observations from all 150 products were combined, and Table 6 was created using Eqs. (1)–(3), where the shaded cells show the general probability for an impact to occur and the nonshaded cells show the joint probability of two impacts to occur. For example, by looking in Table 6, we find that the probability for impact in *Education* is 0.227, and the joint probability for both *Paid Work* and *Human Rights* is 0.123.

Suggestions for how to use this table in a product development setting can be found in Sec. 4.

3.6 Conditional Probability Table. By using the properties of conditional probabilities, Table 7 was created using Eqs. (4) and (5) together with the values in Table 6. Table 7 shows the probability for a second social impact category to occur if one category is known. For example, if we know that there is impact in *Family*, then there is a probability of 0.201 that there is also impact in the category of *Gender* compared with a probability of 0.030 (value from Table 6) if no impacts are known.

Similarly, if there is known impact in one category, the probability of impact for multiple categories can be found. This can be done by using the values found in Tables 6 and 7 together with Eq. (6) to find the probability for several categories occurring.

4 How to Apply the Findings

Engineers sometimes make decisions based on social norms, feelings, and experiences [103]. We believe that this can lead to the creation of products with less social impact than intended.

One way to overcome this is for engineers to refer Tables 6 and 7 that show how social impact categories are correlated in order to find additional impact categories of interest and to use this throughout the product development process.

Below is a method for increasing the potential social impact of engineered products:

(1) Start by looking at the 11 social impact categories found in Table 1.
(2) Identify the obvious social impact categories from Table 1 that corresponds with the design objectives.
(3) To identify nonobvious social impacts, go to Table 7 and find the probability for the co-presence of other social impact categories.
(4) Add the new categories to the design objectives and consider them throughout the design stages.
(5) Evaluate the social impacts of the product throughout the stages of development to ensure that it meets the design objectives.

By following these steps, an engineer can be made aware of social impact categories that could otherwise be overlooked and now broaden the design to include additional social impact objectives, thus achieving a design with an increased impact in the original category together with additional impacts in other categories.

When looking at the shaded cells in Table 6, it is observed that not all social impact categories have the same probability. This falls in line with the findings in the second tier, the industry review [9] where it is clear that the *Health and Safety* category is overrepresented. This shows that there is a potential for work to be done and products to be developed that focus on the categories with low probabilities.

By looking at the different correlations between social impact categories, engineers may be inspired to extend their focus to include additional inputs to extend their product's potential social impact. This consideration can lead to products with greater social impacts than if the correlation had not been considered.

5 Conclusions

In this paper, we have reviewed 150 products and linked them to social impact categories found in literature. We then discovered how the impact categories manifest themselves in the 150 products. We did this to allow us to better anticipate the social impacts of products and to understand how engineered products impact society.

A review instrument was created to help us know how different social impact categories are co-present in products. We then showed how the results from the product review gives us the probability of social impacts. A table for predicting social impact was created using two thirds of the 13,200 data points collected and then validated by using the remaining one third. After the validation, the whole data set was used to create the final prediction table. This table shows the general probability and the joint probability for

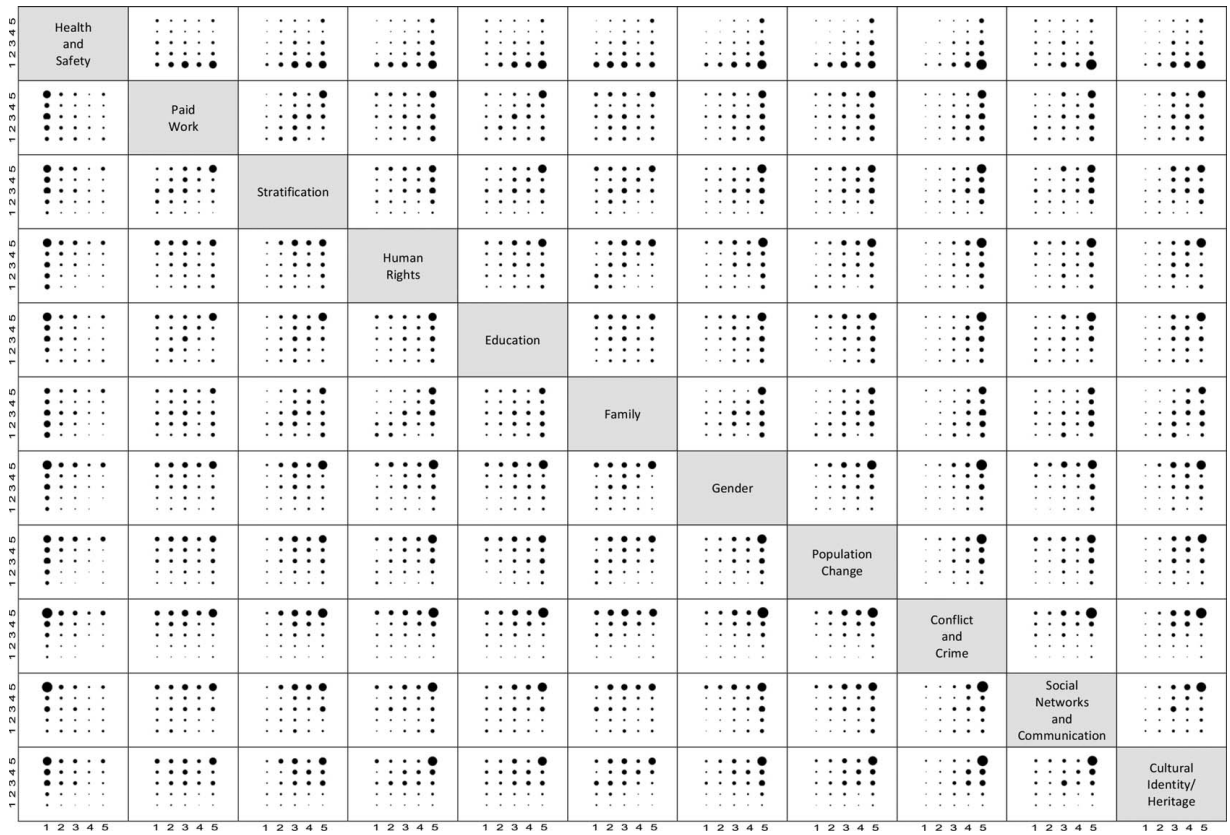

Fig. 5 Scatterplots showing the correlation between the different social impact categories where the size of the dots indicates the number of occurrences for the correlation and where 1 = *Fundamentally Related*, 2 = *Likely Related*, 3 = *Possible Related*, 4 = *Extremely Unlikely Related*, and 5 = *Not Related*. See Fig. 4 for a correlation scatterplot in more detail. The data from all 150 products were used for creating these scatterplots.

social impacts to occur and is also part of the method to be used for improving the social impacts of products.

When using this method, the initial design objective can be widened to include related social impact categories and thus achieve additional impacts in both the original social impact category and other related categories not previously considered. By using this method, we believe that better informed engineering decisions can be made throughout the product development process.

The presented material is limited in the following important ways. Some of the 11 impact categories overlap, and we have not explored what implications that has for engineers (e.g., family and gender impacts). While the social impact categories presented are based on an extensive literature survey [8], the review of products is not extensive nor exhaustive. While we believe that all products have a social impact, and thus an exhaustive survey is not possible, we do believe that the extent of the review can be expanded. The time it took each respondent to complete the product reviews was another limitation, creating a risk of respondent burnout. To combat this when using similar surveys in future research, we would possibly include a greater number of respondents, all of whom would complete only a subset of the survey, thus avoiding the risk of burnout for any one respondent. Another limitation that has not been discussed is the relationship between perceived impact of a product and the actual impact. Finally, the more pertinent limitation is that for the probability table to be accurate, any product that is evaluated must fulfill the selection criteria set up in Sec. 2.2.

Ultimately, we believe that the contribution of this paper lies in the linking of existing products to published social impact categories and how these categories correlate statistically. As such it alerts the engineer to various social impact areas that are not commonly considered during the product development process. Thus, by expanding the views to include related social impact categories, the products that are designed can have a broader social impact.

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