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FMEA-INSPIRED ANALYSIS FOR SOCIAL IMPACT OF ENGINEERED PRODUCTS

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ABSTRACT

Social Impact has been widely discussed by the engineering community, but studies show that there is currently little systematic consideration of the social impact of products in both academia and in industry beyond social impacts on health and safety. This paper illustrates how Failure Mode and Effect Analaysis (FMEA) style analysis can be applied to evaluating the social impact of products. The authors propose a new method titled Social Impact Effects Analysis (SIEA), describe how it is performed, and explain the benefits of performing SIEA.

Keywords

FMEA, FMEA for social impact, Failure Mode and Effects Analysis, Social Sustainability, Products, Impact Assessment, Measurable Social Phenomena, Technology Assessment, Social Impact of Products

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1 INTRODUCTION

Sustainable design encapsulates economic, environmental, and social sustainability. Economic considerations are routinely included in engineering design [1] and environmental considerations are increasingly being considered in design with standards and widely used methodology [2] [3]. While Social Impact considerations are being broadly researched, research reveals that there is a lack of implementation in engineering-centered academia and industry [4] [5].

The lack of implementation of social impact in engineering-centered academia and industry is not due to a lack of methods. There are many methodologies that are used in social science and development fields. Some reasons these methods are not widely used in product development are designers not being aware of methods, methods not being widely applicable, and methods being too complicated or time consuming [4] [5].

Rainock et al categorized the social impact of products into 11 social impact categories [6]:

i Impacts on Conflict & Crime
ii Impacts on Cultural Heritage & Identity
iii Impacts on Education

iv Impacts on Family
v Impacts on Gender
vi Impacts on Health & Safety
vii Impacts on Human Rights
viii Impacts on Paid Work
ix Impacts on Population Change
x Impacts on Social Networks & Communication
xi Impacts on Stratification

Of these, Impacts on Health & Safety are the most widely considered/implemented in engineering practice [4]. One reason for the success of Health and Safety implementation is the use of Failure Mode and Effects Analysis (FMEA) [4].

FMEA is a methodical, qualitative method for evaluating primarily the Health & Safety impacts of part failure [7]. In FMEA designers methodically rate product components, failure modes, and effects to determine risk associated with the product. First designers list out all of the possible failure modes for each component in a system and rate each failure mode by its level of occurrence. Designers then list out the negative effects for each failure and rate the severity of each effect. Designers then rate each failure mode on how easily each failure can be detected and prevented beforehand. The three scores in occurrence, severity, and detectability are used to create an overall risk priority number (RPN). The RPNs of each failure mode and effect are used to determine which failure modes need additional design, manufacturing, or quality control efforts to lower risk to acceptable levels.

The simplicity, consistency, and ability to identify factors leading to failures and corresponding corrective actions early in the design process make FMEA very popular [8]. FMEA is also valued because it can be verified through testing and post-product release as part of a quality management system (QMS).

FMEA generally works well for Health and Safety Impacts, but as is shown in this paper, FMEA is typically only used for analyzing discrete, negative events of a single impact category that equally affect users. In this paper we examine the short comings of FMEA for analyzing the social impacts of engineered products and introduce an FMEA-inspired method that is well suited toward handling the particularities of social impact analysis. This method is known as Social Impact Effects Analysis (SIEA). There are five characteristics of FMEA that make it difficult to use for analyzing social impacts and necessitate the creation and use of SIEA. These are:

I. While FMEA typically analyzes Health & Safety related risks it has been used to analyze other impact categories. Literature reviewed for this found FMEAs that analyzed social impacts in 8 of 11 categories. Impact categories analyzed include: Conflict & Crime [9] [10], Education [11], Family [12], Gender [13], Health & Safety [14] [15] [16], Human Rights [17], Paid Work [18] [19] [20], and Social Networks & Communication [21]. FMEA has also been used to analyze environmental impact [14] [22] [23]. While FMEA has been used to analyze social impacts in 8 categories, the FMEAs reviewed in the literature reviewed for this paper only analyzed between 1-2 impact categories at a time. Products with social impacts typically have impacts in many categories [24].
II. In FMEA the magnitude of failure effects is generally the same for most users. In cases where differences in magnitude occur, FMEA typically considers only the worst case scenario [8]. By comparision, social impacts are highly dependent on context and the differences between users, communities, and environments [25] [26] [27]. Because social impacts depend on both the product and the user the approach taken by traditional FMEA is not sufficient for analyzing social impact [28].
III. FMEA typically deals with the occurrence of negative events and not with the positive events of products [29]. However, products can have positive and negative impacts with large effects on stakeholders [30] [31]. These impacts can be intentional or unintentional and should be considered in the design of a product [28] [32]. Considering only the negative effects of a product is insufficient when considering social impacts during sustainable design.
IV. FMEA deals with the risks of failure events which are by nature uncertain events [33]. These events have varying frequencies and can occur individually or concurrently [34]. The social impact of products can occur continuously across extended periods of time. Social sustainability is based on the notion that products can impact individuals and communities over an extended period of time [35] [36]. The failure-centered approach of FMEA only works well for social impacts of a certain type and limits its ability to evaluate all social impacts.
V. In addition to the uncertainty of random failures that FMEA handles with a detectability metric, other sources of uncertainty exist for the social impact of products such as uncertainty related to product acceptance and use [37], level of impact [28], verification of impact occurrence, and uncertainty related to secondary effects or impacts [38] [39]. FMEA typically only handles uncertainty related to detecting randomly occurring events and is insufficient for handling the range of uncertainties associated with the social impact of products.

The authors have developed SIEA as an analogous method to FMEA to better handle these particularities. It is a systematic social impact assessment tool for utilization in product development. The goal of SIEA is to help designers consider many potential impacts of a product, rank them by importance, and determine specific actions to limit negative impacts and improve the positive impacts of products.

It is important to remember that like any social impact assessment or design methodology the success of SIEA is linked to the people performing the activity. Exploring the social impact of a product works better when those who know the problem deeply, both technically and due to personal involvement, are involved [40]. More diverse teams such as multidisciplinary teams [41] and teams that have diversity of gender, race, and ethnicity perform better [42] [43]. Working with those directly impacted and using a diverse team are recommended as part of performing a successful SIEA.

Section 2 of this paper lists the step-by-step process for performing an SIEA. Section 3 of this paper gives an illustration of an SIEA. Section 4 describes the aspects of SIEA and how they compare to FMEA. These differences are also summarized in Table 4. Section 5 discusses the contributions of SIEA toward helping design teams consider a larger quantity of impacts from a wider range of social impact categories than methods currently in use in engineering-centered academia and industry.

2 Performing a Social Impacts Effect Analysis (SIEA)

In this section the step-by-step process for performing a Social Impacts Effects Analysis is given. An example of an SIEA is shown in Fig 1. and described in Section 3. More detailed descriptions of term definitions and impact ratings are given in Section 4. Section 4 also highlights how SIEA differs from FMEA and how these differences make SIEA better suited for social impact analysis.

Before an SIEA is performed, designers should determine whether or not to perform an SIEA. Products with strong expected impacts, newly developed products, and products being deployed in new areas or for new stakeholders are strong candidates for performing an SIEA [44] [45].

Before performing an SIEA the design team should define stakeholder priorities. Determining stakeholder priorities at this step makes assigning impact magnitudes easier and more accurate. If there are multiple groups of stakeholders with differing priorities, priorities should be defined for each group so impacts can be assigned separately for each.

To perform a successful SIEA, efforts should be taken to form a multidisciplinary, diverse team that includes both technical expertise and experience with the product, effected communities, and social impacts of interest [42].

1. **List Product Attributes:** List all attributes of the design at the relevant detail level. For early stages of design before the product is defined, designers may list product requirements or expected features. In latter stages, the design can be broken down into subsystems, features, components, or attributes. The goal of this stage to list all the possible attributes so that effects and impacts may be assigned to them. See Column C2 in Fig. 1 for examples.
2. **List the Social Impacts of Product Attributes:** List the impacts the product effects have on the stakeholders. See Column C3 in Fig. 1 for examples. If different impacts exist for different stakeholders, assign each impact to its respective stakeholder group. See Column C1 in Fig. 1 for examples.
3. **Categorize Social Impacts:** Social impacts can be assigned to one of major 11 Social Impact Categories: Population Change, Family, Gender, Education, Paid Work, Stratification, Health and Safety, Human Rights, Social Networks and Communication, Conflict and Crime, and Cultural Heritage and Identity [6].See Column C4 in Fig. 1 for examples.
4. **List the Cause of Each Social Impact:** Describe how the product attribute leads to the social impact on stakeholders. See Column C5 in Fig. 1 for examples.
5. **Indicate Each Impact as Positive or Negative:** Define each social impact as having a positive or negative effect on the user. It is possible that a particular impact could be both positive and negative. If this is the case the impact should be listed twice, once as a positive impact and once as a negative impact. See Column C6 in Fig. 1 for examples.
6. **Rank the Magnitude of Each Impact:** Rate the magnitude of each social impact on a scale of 1-10. This is a measurement of how much the impact effects the life of the stakeholder. Table 1 gives an example scale for rating magnitudes. See Column C8 in Fig. 1 for examples.
7. **Rank the Occurrence of Each Impact:** Rate the occurrence of each social impact on a scale of 1-10. This is a measurement of the likelihood of a given impact happening. Different ways of considering impact are given in Section 4.8. Table 2 gives an example scale for rating occurrence. See Column C9 in Fig. 1 for examples.
8. **Rank the Uncertainty of Each Impact:** Rate the uncertainty of each social impact on a scale of 1-10. Uncertainty is a measure of how much uncertainty there is about the occurrence or magnitude of a given impact. Additional Information is given in Section 4.7. Table 3 gives an example scale for rating uncertainty. See Column C10 in Fig. 1 for examples.

Table 1. **Impact Magnitude Rating Table**

Ratings	Description of Impact Rating
1	Little to no impact on the stakeholder
2–3	Minor impact on the stakeholder
4–6	Noticeable impact on the stakeholder
7–8	Major impact on the stakeholder
9–10	Life changing impact on the stakeholder

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17
	SIEA Example Table																
R1	Stakeholder	Product Requirement	Social Impact	Social Impact Category	Impact Cause	Positive or Negative	Continous vs Discrete	Impact Magnitude	Likelihood	Uncertainty	IPN	Assigned Action	Updated Impact Magnitude	Updated Likelihood	Updated Uncertainty	Updated IPN	Increase in IPN
R2	Children of Households in Rural Uganda	Finance lockability allows Fenix to sell to a larger customer base without credit or upfront money as long as they have access to mobile payment	Increased access to electricity available to students	Education	Devices are lower cost which increases availability to students	Positive	Continous	5	6	5	150	Ensure cost of product is in for families with children in school	5	7	6	210	60
R3	Employed members of Household in Rural Uganda		Increased access to electricity available to use for labor	Paid Labor	Devices are lower cost which increases availability to workers	Positive	Continous	7	8	5	280	Ensure cost of product is in affordable range for workers who would benefit from electricity access	7	9	6	378	98
R4	Households in Rural Uganda		Increased access to electricity available to family members	Family	Devices are lower cost which increases availability to all members of a family	Positive	Continous	6	9	7	378	Ensure cost of product is in affordable range for large families	6	10	7	420	42
R5	Women of Households in Rural Uganda		Increased access to electricity available to women in the household	Gender	Devices are lower cost which increases availability to women	Positive	Continous	7	8	5	280	Ensure cost of product is in afforable range for women	7	9	5	315	35
R6	Households in Rural Uganda		Ability of Fenix to lock users devices for non financial reasons.	Human Rights	Fenix International has the ability to lock users electricity access. This can be used for proper purposes, or improper purposes	Negative	Discrete	4	4	3	-48	Add an assistance hotline where users can report false lockouts	2	4	1	-8	40
R7	Employed members of Household in Rural Uganda	Durability allows the device to be transported, or used in rough situations without damage to the device or electrical shock to users	Allows device to be used in portable work conditions as well as harsh industrial or agricultural settings	Paid Labor	The device can withstand work conditions	Positive	Continous	7	7	4	196	Perform Durability Testing for industrial conditions to verify and improve durability	6	8	8	384	188
R8	Children of Households in Rural Uganda		Allows for continual charging of devices in educational settings to aid learning	Education	The device can withstand being used in schools	Positive	Continous	4	8	5	160	Perform Durability Testing for educational settings to verify and improve durability	4	8	8	256	96
R9	Households in Rural Uganda		Accidental Electrical Shock	Health and Safety	The Electronics of the device shock the user	Negative	Discrete	8	3	3	-48	Design protective circuitry to prevent electrical shock incase of device damage or failure	8	2	1	-16	32

Figure 1. **SIEA Example**

Table 2. **Impact Occurrence Rating Table**

Ratings	Description of Occurrence Rating
1	Extremely low occurrence
2–3	Medium low occurrence
4–6	Medium occurrence
7–8	Medium high occurrence
9–10	High occurrence

Table 3. **Impact Uncertainty Rating Table**

Rating for Negative Impacts	Ratings for Positive Impacts	Description of Uncertainty Rating
1	9-10	Little to no uncertainty
2–3	7-8	Low uncertainty
4–6	4–6	Medium uncertainty
7–8	2–3	High uncertainty
9–10	1	Extremely high uncertainty

9. **Calculate Impact Priority Numbers:** The Impact Priority number is calculated by multiplying the Magnitude, Occurrence, and Detectabilty. The sign of the *IPN* corresponds to whether the impact is positive or negative see Equation 1. The *IPN* is used to identify the largest positive and negative impacts of the product. Additional Impact Priority Number calculations have been developed by the author to help designers identify other impacts of interest such as items with high potential for impact but either a low magnitude (Magnitude Priority Number or *MPN*), low occurrence (Occurrence Priority Number or *OPN*), or high uncertainty (Uncertainty Priority Number *UPN*) see Equations 2-4. See Column C11 in Fig. 1 for examples.

$$IPN = Magnitude * Occurrence * Detectability * sign(Impact) \tag{1}$$

$$MPN = (Magnitude - Occurrence) * Magnitude \tag{2}$$

$$OPN = (Occurrence - Magnitude) * Occurrence \tag{3}$$

$$UPN = (Uncertainty) * (Magnitude + Occurrence) \tag{4}$$

10. **Rank Positive and Negative Impacts:** Ranking impacts allow designers to see which impacts have the highest positive and negative values. Ranking of impacts aides designers in determining which impacts need Impact Management Measures. Very low impacts should have social impact management measures to mitigate or prevent the negative impacts. For positive impacts, there are several different approaches. One approach is to assign impact management measures to the highest positive impacts to ensure that the design achieves those impacts. Another approach is to assign impact management measures to the lowest ranking *IPN*s to increase the positive impact. A third approach is to assign impact management measures to important impacts that are high ranking in one category such as high-magnitude/low occurrence or high-occurrence/low-magnitude impacts. All approaches have merit and may be used by the design team. These approaches are discussed more in depth in Section 4.5.
11. **Social Impact Management Measures:** Impact Management Measures are specific actions assigned to team members to improve positive impacts or decrease negative impacts. These design activities are designed to change either the magnitude, occurrence, or uncertainty of the impact. See Column C12 in Fig. 1 for examples.
12. **Re-score Magnitude, Occurrence, and Uncertainty for Impacts with Management Measures:** Adjust Magnitude, Occurrence, Detectability scores as necessary to reflect expected changes as the result of Impact Management Measures. See Columns C13-C16 in Fig. 1 for examples.
13. **Follow Up:** Perform follow up to ensure that Impact Management Measures have the intended effect.

3 Illustration/Example

Figure 1 shows several rows of an example SIEA performed by the authors. The exercise examined the social impacts of a modular solar charger designed for use in rural Uganda. Due to size constraints only eight rows of the example SIEA are listed in this paper, however the full example is available at design.byu.edu.

Column 1 lists the stakeholders/users of the solar charge which in this example are: households in Uganda, children in the households, women in the households, and employed members of the households. Column 2 lists product requirements or features such as the mobile payment and mobile locking of the modular solar charger. Column 3 lists social impacts of the product feature such as increased electricity access for work purposes, for educational purposes, and increased electricity access for women in the households. Column C4 lists which impact category each impact belongs to such as Paid Labor or Education. Column C5 lists the impact causes such as the mobile payment availability lowering monthly payment costs which makes the device more accessible. C6 lists whether designers viewed each impact as positive or negative such as increased electricity being a positive impact, and the ability of the solar company to lock users out as a negative impact. Columns C6, C7, and C8 are the designer ratings for impact magnitude, likelihood, and uncertainty. Column 11 shows the calculated Impact Priority Number *IPN* for each impact. These *IPN*s were used by the authors to rank impacts by priority and assign actions for increasing positive impacts and decreasing negative impacts. Column C12 lists suggested impact management measures such as ensuring customer service assistance is available to help customers who are mistakenly locked out of their solar chargers. Columns C13, C14, and C15 list new rankings for impact magnitude, likelihood, and uncertainty after suggested actions are taken. Column C16 lists the new scores and C17 lists the expected improvement due to the impact management measures.

The exercise took 3 hours to complete and analyzed 42 potential impacts related to 11 product attributes in 7 social impact categories (Education, Family, Gender, Health and Safety, Human Rights, Paid Labor, and Social Networks and Communication). This shows the ability of SIEA to aid designers in considering a wide range of impacts from different social impact categories.

This exercise also helped designers see how each of 4 different stakeholder groups were affected differently by the product (Households in Uganda, Employed Members of Households, Women in Households, Children in Households). The activity also connected the 42 potential impacts to 11 product attributes. These connections help designers understand how product performance leads into impact as well as the trade-offs and relationships between product performance, impact, and multiple stakeholder groups.

And finally, the calculation of Impact Priority Numbers allowed all 42 potential impacts to be ranked to help determine designer priorities for maximizing positive impact. All 4 Impact Priority Numbers in Section 2.10 (Traditional Impact Priority Number, Magnitude Priority Number, Occurrence Magnitude Number, and Uncertainty Magnitude Number) were calculated to find the highest overall positive and negative impacts as well as high potential targets for improving the magnitude, occurrence, and uncertainty.

The largest positive impacts were the impact of increased electricity access due to the cost of the charger. The largest negative impact was the loss of electricity due to being remotely locked out of their charger when they should have access, and electrical shock due to the charger being damaged. The largest opportunity for increasing impact through occurrence was increasing the occurrence of electricity access for women related to the modularity of the solar charger. The largest opportunity for increasing impact through magnitude is the impact on paid labor of having port types necessary for use in electrical tools and equipment. The largest opportunity to increase impact by decreasing uncertainty is the ability to reliably charge all the communication devices a household would need.

These rankings illustrate the ability of SIEA to help designers not only create a large list of potential impacts, but also to rank and prioritize which impacts need additional consideration in the design process. Focusing on the impacts identified increased the overall impacts by both decreasing negative impacts and increasing positive impacts of the product.

4 Highlighting Differences Between SIEA and FMEA

This section describes the attributes of SIEA in greater detail and how they compare to FMEA. These differences demonstrate the need for SIEA as a seperate method from FMEA and show that SIEA is better suited for analyzing social impacts. These differences are summarized in Table 4.

4.1 Stages of Design

Like FMEA, SIEA can be implemented across all stages of design from concept development, to subsystem design and refinement, to manufacturability, and even post release maintenance and disposal. In the concept stage, SIEA analyzes the desired impacts and product requirements. As the design becomes more defined, SIEA can analyze the product on a system, subsystem, or component level. Process SIEAs could be performed as well. Additionally, there are impacts associated with implementation practices that SIEA could potentially analyze although Social-Life Cycle Assessment already exists for that very purpose [30] [46] [47].

4.2 Social Impacts Considered

SIEA aims to help designers consider more relevant social impacts in a wider range of impact categories than methods currently practiced in engineering such as FMEA. SIEA encourages designers to consider more social impacts by systematically listing social impacts for every aspect of the product and by asking them to consider 11 social impact categories. Products typically have impacts in multiple social impacts categories [24]. SIEA guides designers in considering a broad range of impacts across categories as opposed to the typical 1-2 social impact categories usually explored in FMEA. The example in Section 3 illustrates this principle for an SIEA performed on a modular solar charger.

4.3 Industry Specific Lists of Impacts

One feature of FMEA is that design teams can use an industry specific list of effects to more quickly and completely analyze potential product effects. Currently, no lists of impacts have been specifically developed for SIEA. Other social impact assessment tools have developed lists of common social impacts that designers could borrow for use in SIEA. Both Social Life Cycle Assessment and Social Impact Assessment Social Life Cycle Assessment have created lists that could be utilized [25] [30] [31] [46] [47] [48] [49]. Utilizing common lists will make it easier for designers who are not familiar with social impacts to consider impacts they might not have previously considered.

4.4 Handling of Multiple Stakeholders

Social impacts depend on both the product and the user [28]. Individuals have many differences including differences in physical attributes, access to resources, cultural upbringing, needs, desires, and priorities. Because social impacts are closely linked to stakeholder values, SIEA starts by attempting to identify and understand the priorities of major relevant stakeholders. This can be done through a variety of methods such as using personas, or including stakeholders in participatory or co-design [54] [55] [56].

SIEA handles stakeholder differences by evaluating impact magnitudes separately for each major stakeholder group. This helps design teams consider the most important impacts for each stakeholder group and understand trade-offs between stakeholders. This information helps design teams handle trade-offs well and create a product with desirable impacts [57].

4.5 Positive and Negative Impacts

SIEA assigns each impact as either a positive or negative impact which is a notable deifference compared to FMEA Considering impacts as positive or negative helps designers know which positive impacts need to be increased and which negative impacts need to be mitigated or prevented [28]. Whether an impact is considered a positive or negative can vary for stakeholders, as a product may produce positive impacts for one user and negative impacts for another [6] Industrial equipment, for instance, may increase profit for its owner, but could pose a safety risk to users, and create pollution and noise that negatively impacts the community. Often times these impacts are paired and lead to trade-offs.

Additionally, products often have secondary effects where the benefit of a product leads to a change in behavior which creates additional impacts [58]. For example, farming equipment that improves farm output could improve wages for employees of farmers that own the equipment, or the increase in efficiency could lead to fewer employees or other laborers. Increased output could negatively impact competing farmers. Positive social impacts may produce negative secondary impacts, and negative social impacts may produce positive secondary impacts. Secondary effects are important to consider because they are often missed and unconsidered secondary impacts have been observed as a source of project failure in global development projects [38] [39].

Considering both positive and negative impacts simultaneously offers an improvement to several current risk management methodologies that only consider negative impacts such as FMEA [29]. The assignment of positive or negative also goes toward calculating the Impact Priority Number which is used for ranking and prioritizing product impacts. There are differences in how positive and negative impact scores are ranked and the strategies designers use to increase positive impact and decrease negative impacts. These differences are discussed in greater detail in Section 4.11

4.6 Discrete and Continuous Impacts

Several methods used in engineering handle only either discrete events such as FMEA [33] or the continuous impacts of products. SIEA has been designed to deal with both the discrete and continuous impacts of products. This is important because events that cause impacts can either be discrete such as a medicine relieving symptoms for a few hours or continuous such as the clean water a well supplies to a village 24 hours a day. Additionally, discrete events can create lasting continuous impacts such as an injury caused by a product having lasting health effects. Events that continuously provide an impact while in use might also provide little benefit after use is ended such as an emergency shelter. Some products might not be used continuously, but the availability of use provides an impact such as a cell phone that only provides benefits while in use, but the ability to use the phone at any time creates a continuous positive impact.

The complex nature of discrete and continuous impacts and effects can make it difficult to compare and rank quantities typically used in FMEA such as occurrence detectability. The ways that SIEA addresses these concern are discussed in greater detail in sections 4.8 and 4.9.

4.7 Impact Magnitude

In SIEA, impacts are rated for magnitude on a scale of 1-10 with 1 being a low magnitude impact and a 10 being the highest magnitude impact. What constitute a high or low magnitude impact depends on the user, the impact category, and the industry of use [8]. Table 1 in Section 2 gives an example of a generic magnitude scale. Magnitude ratings are used to help the team understand what level of impact the effects of a product have to guide them in their design efforts [7] [8]. These numbers are qualitative and the exact number is not as important as a consistent scale and ordering within the team as it is the order and relative magnitude that guides the ranking and ordering of impacts [7].

4.8 Occurrence

Although all impact causes can be thought of as continuous or discrete, all impact causes and impact effects can be described as having an occurrence or likelihood. Mathematically this is a probability or percentage between 0-1 or 0%-100%. Defining occurrence in this way is robust mathematically, but is potentially problematic in the context of occurrence ratings that occur in

Table 4. **FMEA and SIEA Comparison**

Attributes	FMEA	SIEA	Section of Paper
Stages of Product Development [50]	Concept Development, Subsystems Engineering System Refinement	Opportunity Development, Concept Development, Subsystems Engineering, System Refinement	4.1
Social Impacts Considered	Generally used for Health & Safety or Business Risks. FMEA has been used for 8 of 11 Social Impacts [6] but only 1-2 at a time. Conflict & Crime, Education, Family, Gender, Health & Safety, Human Rights, Paid Work, Social Networks & Communication.	Designed to be used for 11 social impact categories: Conflict & Crime, Cultural Heritage & Identity, Education, Family, Gender, Health & Safety, Human Rights, Paid Work, Population Change, Social Networks & Communication, and Stratification [6]	4.2
Industry-Specific Standards	Industry specific standards exist for FMEA [7] [51]	No industry specific standards exist	4.3
Industry-Specific lists of Common Impacts	Industry specific lists of common failure modes exist [14] [52] [53]	No SIEA specific lists of common impacts exists. Social Impact Assessment and Social-Life Cycle Assessment lists may be used for SIEA. [48] [31] [25] [46] [47] [30] [49]	4.3
Multiple Stakeholders	Failure modes are often assumed to have the same effect on all stakeholders	Impacts are analyzed separately for each stakeholder group	4.4
Positive & Negative Impacts	FMEA generally deals with failures or negative impacts. [29]	Social Impacts can be positive or negative. SIEA handles both positive and negative events.	4.5
Discrete & Continuous Impacts	FMEA typically only deals with the effects of discrete events [33]	SIEA analyzes the impact of both discrete and continuous events.	4.6
Impact Magnitude	Failure mode effects are typically rated on a Severity Scale of 1-10	The effect impacts have on stakeholders are rated on a Magnitude Scale of 1-10.	4.7
Impact Occurrence	Failure Occurence is typically evaluated on a 1-10 scale,	Impact Occurrence is evaluated on a 1-10 scale. Multiple scales may be used and include linear, logarithmic, and qualitative scales.	4.8
Uncertainty vs. Detectability	Failure Detectability is typically evaluated on a 1-10 scale	Impact Detectability is a specific type of uncertainty. Other types of uncertainty are considered, and uncertainty is evaluated on a 1-10 scale.	4.9
Impact Priority Number	The Risk Priority Number (RPN) is calculated by multiplying the Severity, Occurrence, and Detectability	The Impact Priority Number (IPN) is calculated by multiplying the Magnitude, Occurrence and Detectability. Negative impacts are multiplied by negative 1. Additional Impact Scores may be calculated for prioritizing impacts.	4.10
Impact Management Measures	Resources are dedicated to mitigate risks with an RPN above a given threshold.	Resources are dedicated to impacts with a negative IPN below a given threshold to raise the IPN to acceptable levels. Resources are dedicated to improve the most important positive impacts as determined by the design team.	4.11
Secondary Effects	Secondary Effects are considered for each failure to capture additional failure modes or effects. Likely combinations of multiple failure modes are considered	Secondary effects are considered for each impact consider additional impacts.	4.5
Relationship Between Impacts	Failure modes and causes are listed by component. No additional relationships are considered.	SIEA shows relationships between impacts on different stakeholders. SIEA also shows the trade-offs between positive and negative impacts resulting from the same product component.	4.12

FMEA and other methods. The main two issues with this are that impacts can occur across a broad spectrum of occurrences, and the value judgements associated with assigning an occurrence number vary depending on the individual impacts.

For example, a knee brace could provide stability and improved healing for 19 out of 20 patients, cause irritation in 5 out of 20 patients, and lead to a serious accident by snagging on heavy equipment or moving objects 1 time per 200,000 hours of patient use. Linear, and potentially even logarithmic scales may have difficulty providing the right level of resolution across the potential impacts of a product. Furthermore, what qualifies as a low or high occurrence depends on the individual impact. In the previous example, the 1 serious injury per 200,000 hours of patient use might be considered a high occurrence event in need of mitigation while the 5 in 20 occurrence of irritation might be considered a low occurrence not in need of additional design consideration. Some of these issues are resolved by the overall impact score accounting for the magnitude and detectability of impacts, however some issues may remain.

There are several approaches to handling these irregularities. The authors present four options that have different strengths and drawbacks that provide flexibility for the best use in different application or situations:

1. One option is to use a linear occurrence scale related to the mathematical probability of occurrence and a range that encompasses the impacts identified. This approach is straightforward and intuitive mathematically. Potential scaling issues may be resolved with additional impact ranking metrics discussed in Section 4.10.
2. Another approach is to use the mathematically occurrence of probability on a logarithmic scale. This approach handles large ranges of occurrence well and provides good resolution across such large differences. However this approach is slightly less intuitive and may involve additional calculations.
3. A different approach would be to consider the occurrence in a qualitative manner instead of a strictly mathematical assignment. As discussed previously, whether an impact is considered a low occurrence or high occurrence depends on the impact itself. This approach allows designers the flexibility to make these value judgements. This approach might not be as mathematically rigorous or repeatable, but may be a more appropriate approach when the effects of product impacts span a very large range. This approach is demonstrated on Table 2 in Section 2.
4. A fourth approach borrowed from design FMEA for use in design SIEA is to rank occurrence based on the likelihood that the design team can design the product to achieve the desired level of impact. This approach is applicable early in the product design before mathematical probabilities can be known and helps the design team focus on the areas of design that need the most attention to achieve the desired impact.

4.9 Detectability versus Uncertainty

One important aspect of social impact is uncertainty [59]. There are several types of uncertainty associated with social impacts. For designers there is uncertainty about the actual impact a product has on the lives of users [28]. There also exists uncertainty about the adoption or acceptance of the product [37]. Additional uncertainty comes from the potential for secondary impacts or effects [38] [39].

There are several sources of uncertainty of impacts on the user side as well. There is uncertainty associated with the occurrence of random events. In traditional FMEA this is referred to detectability, and increasing the detectability decreases uncertainty by allowing users to foresee a potential failure before the negative effects of the failure occur. There is also uncertainty for the user about whether or not a product is leading to a personal impact. For example, the health benefits of clean water or an improved cookstove might not be immediately apparent to users. This type of uncertainty can affect the likelihood of an individual to use a product [60]. This type of uncertainty is also challenging for those who wish to measure or quantify the impact of products.

As designers, it is desirable to lower all of these uncertainties. Areas of high uncertainty signal a need for design resources to reduce uncertainty. When it comes to ranking uncertainty for use in risk there are several possible approaches with varying strengths and weaknesses. These approaches are as follows:

1. Focus on only one type of uncertainty. This approach only considers one source of uncertainty at a time. This is a simple approach that also tailors to the different stages of design. In conceptual stages designers may rate the uncertainty associated with designing the product, and later stages may then progressively focus on the uncertainty associated with levels of impact, product acceptance, and verifiability of the impact occurring.
2. Consider multiple sources of uncertainty. This approach ranks each type of uncertainty separately. This approach is beneficial in that it considers many types of uncertainty, however it increases the time required to perform an SIEA, and could complicate *IPN* rating calculations and ordering.
3. Consider only the largest uncertainty. While several sources of uncertainty exist for all impacts, some may be of greater concern for individual product impacts. Ranking the largest source of uncertainty for each impact lowers the amount of rankings and calculations needed, but it adds complexity as it requires designers to compare different sources of uncertainty mentally.
4. Use a holistic approach. This approach relies on the intuition and experience of users to consider the overall uncertainty from all sources. This approach is not as well defined, but

it has the potential to cover the breadth of uncertainty types without requiring the time put into a deep analysis of each type individually.

4.10 Risk Priority Number and Impact Priority Number

The Impact Priority Number (*IPN*) is a measure of the overall importance a given impact is. The IPN is calculated by multiplying the magnitude, occurrence, detection, and the sign of the impact. IPNs can take values between -1000 to 1000. These IPNs can be thought of as Negative Impact Priority Numbers (*NIPN*) ranging between -1000 to 0, and Positive Impact Priority Numbers (*PIPN*) ranging from 0 to 1000. For negative impacts, values close to 0 are desired and for positive impacts IPNs close to 1000 are desired.

This type of calculation is used for FMEA Risk Priority Numbers *RPN*. Despite wide use of the concept, there are several criticisms of the common *RPN* equation in the literature. These criticize the scaling, comparability, and consistency of RPNs [61] [62] [63] [64]. Other suggested calculations include: category weighting, fuzzy *RPN* functions, fuzzy adaptive resonance algorithms, exponential *RPN*, and utility priority numbers [61] [63] [64] [65] [66].

In addition to the traditional *RPN* score, the authors have created additional impact score calculations for helping designers identify items with high impact magnitude but low occurrence, low impact magnitudes with high occurrence, and high uncertainty impacts. These additional measures can help designers identify which type of impacts they wish to focus their attention on. These calculations are given equations 2-4 in Section 2 Step 10.

4.11 Impact Management Measures

The ultimate goal of SIEA is to consider many of the possible impacts and rank them so that resources can be dedicated to the most important impacts [61] [63]. After impacts have been ranked by *IPN* the design team assigns specific actions to team members. These corrective actions aim to lower negative impacts and increase positive impacts by changing the magnitude, occurrence, or uncertainty of selected impacts [65]

Multiple possible corrective actions can be taken that may have different effectiveness and costs. The design team decides which corrective action would be most appropriate and assigns the action to a specific team member [67]. The right corrective actions in the early stages of design can prevent more costly corrective actions later [67] There are several ways to determine how many risks to assign impact management measures to. These include using an *IPN* threshold, assigning actions to a top percentage of impacts, using a screening matrix, or using a graph of *IPN*s to find the inflection point for impact priorities [7] [68] [69].

4.12 Relationships Between Impacts

Social Impact Categories have been observed to be correlated to each other with differing strengths [24]. In addition to these relationships, there are trade-offs that design teams will have to navigate. These trade-offs include trade-offs between impact categories [24] [70], trade-offs between technical performance and social impacts [71], and impacts on stakeholders [72].

SIEA can be used to reveal these trade-offs through the associated Impact Priority Numbers. These can be identified by looking at the relationship between primary impacts and secondary impacts, or by looking at paired positive and negative impacts. The IPNs also give designers a way to look at the relationships between impacts, product attributes, and stakeholders. One way of visualizing these tradeoffs is by organizing them into a matrix showing which product attributes relate to which impacts [73] Another method for identifying trade-offs is sorting the tables by category, stakeholder, or product attribute.

4.13 Benefits of Differences from FMEA

SIEA borrows aspects of FMEA that are attractive for analyzing the social impact of engineered products such as a structured methodical approach and qualitative rankings that allow for the comparison of impacts. Several aspects of FMEA, however, limit its potential for use in social impact assesment. SIEA improves upon FMEA by handling impact differences for multiple stakeholders and for considering social impacts from a broader range of categories. SIEA also can handle both continuous and discrete impacts as well as positive and negative impacts.

5 Discussion and Concluding Remarks

SIEA improves on the ability of current methods used in engineering to analyze social impact by handling impacts from a wide range of social impact categories, with different effects on stakeholders, both positive and negative, continuous and discrete, and with varying degrees of uncertainty. These characteristics combined with the methodical approach of SIEA make SIEA usable to engineers with little social impact experience [4].

SIEA also aims to increase the usability of social impact analysis by using a systematic approach that connects impacts to product attributes and. Additionally, using a method similar to current practices and avoiding unnecessary complexity will help increase implementation and adoption [74]. SIEA is also an attractive method because the qualitative approach borrowed from FMEA is less costly and thus more likely to be implemented then other social impact assessment methods that require large amounts of data [75].

Future work includes additional experiments to verify and quantify the ability of SIEA to help designers in these areas. Potential metrics to demonstrate the effectiveness of FMEA include measuring the quantity, variety, and novelty of social impacts considered by SIEA and comparing the results to other design methods and social impact analysis methods.

Other opportunities to build upon the contributions of SIEA include creating a list of common social impacts to aide designers in considering a larger quantity of impacts from a wider range of social impact categories. Developing supplementary educational materials such as SIEA templates, presentations, and tutorials to aid with the implementation of SIEA also has the potential to increase the usability and effectiveness of SIEA.

In conclusion, SIEA has potential as a tool for helping designers consider the social impact of their products. It combines desirable features of FMEA that contribute to the wide use of FMEA in engineering industry and academia with the ability to better handle the complex nature of social impacts. The authors hope that these attributes will make social impact analysis more accessible and effective to aid in the development of products with improved social impact.

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