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Integrating Toxicity Reduction Strategies for Materials and Components into Product Design: A Case Study on Utility Meters

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ABSTRACT

Using RIO Tronics utility meter products as an industrial case study, the numeric Fraunhofer Toxic Potential Indicator (TPI) assessment tool is used to determine high impact materials with the aim of reducing the content of inherently toxic substances in these products. However, because product redesign with alternative materials affects entire components, overall component toxicity potential must also be explored. To achieve this, material TPI scores are aggregated into component TPI scores by 2 methods: 1) the Sum-Weighted Component TPI method, which considers the mass of materials in the component to assign an overall score, and 2) the Max Component TPI method, which scores the component with the highest impact material. With consideration of uncertainties from materials' toxicity information and mass estimates, key results from both scoring methods prioritized components that contain acrylonitrile-based polymers, polyvinyl chloride (PVC), and stainless steel. Furthermore, an alternative materials assessment is carried out to identify less-toxic substitutes to meet cost and technical constraints. Substitute materials such as Al alloys for stainless steel and high-density polyethylene for PVC show promise for a combination of toxicity reduction and cost-effectiveness. The new screening methodology described can help product designers systematically benchmark toxicity potential in parallel to cost and functionality. Integr Environ Assess Manag 2013;9:319–328. © 2012 SETAC

Keywords: Design for environment   Environmentally benign materials   Toxics use reduction   Materials selection   Toxic potential   Uncertainty analysis

INTRODUCTION

The scope of engineering design has now evolved to consider not only material function including mechanical, thermal, optical and electrical properties, and economic performance, but also inherent material toxicity to humans and ecosystems (Holloway 1998; Thomas and Graedel 2003; Ogunseitan and Schoenung 2012). To date, a rising challenge in materials selection and product design is integrating reasonably straightforward toxicity assessment tools for preliminary screening and prioritization of various materials and components in products to guide toxics use reduction. Although toxics use reduction is not a new concept (e.g., the Commonwealth of Massachusetts established the Toxics Use Reduction Act in 1989) (MassDEP 2012), it has gained momentum in recent years with the implementation of the Green Chemistry Initiative in the State of California (DTSC 2012) and with the establishment of US Environmental Protection Agency (USEPA) Design for the Environment (DfE) alternatives assessment criteria (USEPA 2011). Separately, the state of Washington is leading a coalition of 7 other member states (California, Connecticut, Massachusetts, Michigan, Minnesota, New York, and Oregon) that make up the Interstate Chemicals Clearinghouse to initiate safer product development guidance for companies (Washington State Department of Ecology 2012).

Traditionally, a prominent comparative approach is life cycle assessment (LCA) with which a product designer can systematically and quantitatively benchmark human health and environmental impacts across material life cycle stages (Finkbeiner et al. 2006). In many situations, however, such comprehensive LCA studies covering upstream and downstream inventory impacts require significant time-investment, data gathering, and expertise, making LCA application particularly challenging for companies with fast product turnover rates (e.g., electronics and semiconductor industries) (Keoleian 1993; Millet et al. 2007; Yen and Chen 2009). Outside of these issues, established LCA methodologies also have additional complications with a range of embedded uncertainty concerns that need to be addressed for product

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evaluations (Williams et al. 2009). Deriving from hazard traits of materials used in products, hazard-based toxicity screening, although not meant to replace LCAs, is developed as another assessment option to simplify and expedite the materials selection process, especially before product (re-) designs have been finalized, in an effort to reduce the extent of toxic substance use. These tools are particularly useful to quickly screen materials of more complex product systems such as electronics or other technologically advanced consumer goods.

Previous work in designing toxicity screening tools include the Use Cluster Scoring System (UCSS) developed by the USEPA (USEPA 2010), Ashby's CES EcoSelector materials selection software (Granta 2009), Clean Production Action's Green Screen for Safer Chemicals (CPA 2009), and Fraunhofer's Toxic Potential Indicator (TPI) method (Nissen et al. 1998; Yen and Chen 2009). All of these tools provide comparative benchmarking of environmental burden and prioritization of high impact substances. Although relevant, a key limitation of the UCSS method in the context of engineering design is that it uses only a qualitative low to high rating system, making it difficult to differentiate between materials classified with the same rating. The CES software is only focused on the safety labeling of materials derived from US Food and Drug Administration criteria, which neglects other environmental toxicity classifications. Despite being very comprehensive in capturing the toxicity potential of substances by taking into account a wide spectrum of human health and ecological toxicity information, the Green Screen method provides only a qualitative output to compare materials with its tiered benchmark 1-to-4 ranking approach. In contrast, the TPI method, used in this research, is a tool that allows numeric conversion of available environmental, health and safety information for substances into a single value toxicity potential score ranging from zero to 100 points, thereby providing increased granularity of results for a wide variety of substances.

In context of uncertainty, for all of the aforementioned toxicity screening toolsets, data gaps are a significant issue due to their dependence on published toxicity information used for calculating ratings, yet these uncertainties are rarely addressed directly. From this perspective, a numeric scoring system such as the TPI can be particularly helpful to quantitatively check the sensitivity of results triggered by possibly unreliable or unavailable input parameters. Furthermore, Material TPI scores allows for enumeration of Component TPI scores, which are needed for component selection in product redesign (Ashby 2010), as described in this research. The numeric Component TPI scores also facilitate evaluation of uncertainty when the materials composition within components is approximated. Examination of the literature indicates that component selection, especially the aggregation of material scores into a component score, and uncertainty analysis have not been previously addressed in a comprehensive manner.

Recognizing the challenges associated with reducing toxics in complex products that consist of multiple components, this collaborative research effort between the Industrial Ecology Research Group (IERG) from the University of California, at Davis and Irvine, and an industrial partner (RIO Tronics, a producer of utility meter products) (RIO Tronics 2012) aimed to develop an appropriate toxicity screening methodology to guide component (and ultimately material) selection and to implement the methodology with a case study on commercial products. In the past, initial use of the TPI has been applied to evaluate electronic products such as metals in mobile phones (Wu et al. 2008), electronic solder types (Fujino et al. 2005), electronic ignition system components (Yen and Chen 2003), and light emitting diodes (LEDs) (Lim et al. 2011) to show varying degrees of data transparency and completeness. For toxicity screening, this is one of the first case studies, of which we are aware, where the Bill-of-Materials (BoM), i.e., details on the components, is completely and openly described for the entire electronic products assessed (rather than as a simplified list of material content), where aggregation of materials TPI scores into a component-level TPI score is quantitatively analyzed, and where uncertainty issues are explicitly addressed. Previous relevant BoM analyses have mainly been applied in an LCA context (Socolof et al. 2002; Cooper et al. 2009; Duan et al. 2009) and have not focused on material toxicity potential. Utility meter products are fitting to apply this methodology because these products represent sufficient material and component complexity to illustrate the intricacies of using such a screening tool during alternatives assessment. Recommendations are also included here based on feasible material substitutions while accounting for cost and technical performance requirements for prioritized components. This analysis illustrates the advantages and challenges of using established DfE tools such as the TPI method to guide alternative material recommendations that support alternative component selection for a range of real products.

METHODS AND DATA

Utility meter products

In this industrial case study, 3 types of utility meters sensors and 1 remote display unit are analyzed based on their materials composition, component design, and their associated toxicity potentials. The names of the products and their applications include: 1) PulsePoint: for domestic gas meters, 2) RotaRead: for rotary gas meters, 3) RegistRead: for dial indexes on both gas and electric meters, and 4) Remote Consumption Display (RCD): a remote meter liquid crystal display (LCD) unit connectable to other meter sensors.

To clarify methodology application, we highlight the results for the PulsePoint, whereas detailed assessment results for other products are provided in the Supplemental Data. Photographs of all products are also provided in the Supplemental Data Figure S1.

As a first step in our analysis, RIO Tronics provided the BoM list of components present in each of the products to be investigated for toxicity potential. With the BoM, we estimated the mass of each material in a given component based on information provided by the component manufacturer (RIO Tronics or original component producer) and estimates made from dimensional calculations from component specifications.

A note should also be made here to distinguish between "component" and "material." A material represents a distinct homogeneous phase such as specific polymers and metals that constitute a particular component. Products are comprised of different components such as housings, shells, and printed wiring boards (PWBs). Components may generally consist of multiple materials.

Fraunhofer TPI method for Material TPI

Detailed descriptions of the TPI's computational structure are published in various references (Yen and Chen 2009; Lam et al. 2012). We assessed each product's component list by applying the TPI method to score every material in each component. The TPI method requires 3 main input variables to reflect health, environmental, and other safety considerations for substances including:

- Occupational exposure limits based on maximum workplace concentration (MAK) for noncarcinogens or European Union (EU) classifications for carcinogens
- Water hazard classification (WGK) and
- Risk phrases (R-phrases)

Representing human health toxicity, MAK values stand for the maximum air concentration of a substance allowed in the workplace that does not cause an adverse effect for normal 8-h work durations (DFG 2011). Carcinogenic substances are treated differently because there is no threshold below which these substances are harmless. These are instead referenced by their carcinogenic potential as categorized by EU criteria (EC 1967).

The TPI method integrates the water pollution classification value, WGK, to represent environmental toxicity potential. Based on German environmental legislation (UBA 2011), substances can be classified as nonhazardous, slightly hazardous, hazardous or very hazardous to water.

R-phrases are used to capture a multitude of health and environmental hazards and safety issues presented by a material within the TPI method (EC 2001). These can range from substance flammability potential to ecosystem impact potential. A substance can be assigned multiple R-phrases to describe the various hazards posed. R-phrases contributing to human health and environmental categories are separately assigned to avoid overlap and double counting of toxicity effects. For this, the most sensitive contribution from either MAK and WGK values or R-phrases is used to represent human and environmental categories, respectively (Yen and Chen 2009).

With the exception of MAK values, qualitative categorizations (e.g., EU carcinogenic categories, R-phrases, and water hazard classes) are aggregated quantitatively into TPI scores for toxicity screening. In the case study, material toxicity information for WGK, MAK (or EU carcinogenic classification), and R-phrase values are compiled from the German Institute for Occupational Safety and Health database on hazardous substances (IFA 2012). A software version of the TPI method (TPI-Calculator) (Fraunhofer 2002) is used to calculate Material TPI scores. By convention, the units of outputted Material TPI scores are referred to as TPI per milligram (mg) of substance.

Note that in determining Material TPI scores for polymers, toxicity information for their monomer form or precursor material is used (e.g., polyvinyl chloride [PVC] is assessed as vinyl chloride, nylon-6 as caprolactam, and polyethylene terephthalate (PET) as terephthalic acid) in the TPI method. Metal alloys are assessed based on the metal constituents present. These materials have been evaluated in this manner because of gaps in reported toxicity data. An acknowledged limitation of using surrogate materials is that realistic exposure impacts for these materials may be overestimated (e.g., metal alloys) (USEPA 2007). However, in hazard assessment research, there is precedence for the use of surrogates to evaluate hazard for these materials due to lack of complete toxicity information (Swanson et al. 1997; USEPA 2007; Lithner et al. 2011). Furthermore, because this is a hazard screening approach, it is preferred to apply the more conservative scenario for assessing these materials, instead of assuming a value of zero for the Material TPI scores.

Derivation of Component TPI from Material TPI

Further development is required to aggregate material toxicity scores to represent components, because these components, which control the performance of the product, generally contain more than one material. A simple mass-weighted summation of toxicity scores from component materials can potentially obscure the environmental impacts of diluted or low-mass but high-toxicity-potential materials, leading to inappropriate priority setting for components within products. For example, minor quantities of additives in plastics (e.g., bisphenol A and phthalates) (Pearson and Trissel 1993; Yamamoto and Yasuhara 1999) may leach out during use or disposal to cause concern. To address these issues, Material TPI scores for the materials in the products are aggregated into Component TPI scores using 2 comparable methods, the Sum-weighted Component TPI method

$$\mathrm{TPI\_sum}_k = \sum_j m_{j,k}\mathrm{TPI}_{j,k}, \tag{1}$$

where $\mathrm{TPI\_sum}_k$ is the total sum of mass weighted toxicity potential for component k; $m_{j,k}$ is the mass of material j in component k; and $\mathrm{TPI}_{j,k}$ is the toxicity potential of material j in component k (i.e., Material TPI), and the Max Component TPI method

$$\mathrm{TPI\_max}_k = \max(\mathrm{TPI}_{\mathrm{all\_materials},k}), \tag{2}$$

where $\mathrm{TPI\_max}_k$ is the highest toxicity potential material present in component k; and $\mathrm{TPI}_{\mathrm{all\_materials},k}$ is the vector of toxicity potentials representing all materials in component k.

The Sum-weighted Component TPI method allows ranking components while taking into account the mass of materials causing toxicity potential. The Max Component TPI method identifies the highest toxicity potential material within a component and scores the entire component based on its presence, regardless of its mass within the component.

Uncertainty in materials composition estimates and TPI scores

The materials composition data quality for components within each product varies, and complete toxicity information required for computing TPI scores are not available for some materials. To reflect the reliability of our results, we integrated sensitivity analyses into the component assessments. To achieve this, rubrics are developed to assign uncertainty ratings for the various input parameters used, specifically, component composition and Material TPI scores.

Depending on how material masses are derived within product components, a label of low, medium, or high uncertainty rating is tracked for each component. Low uncertainty is assigned when the mass of a component and all its material mass information are provided by the manufacturer. Medium uncertainty is assigned when the mass of a component is provided by the manufacturer and the material masses are calculated based on dimensional estimates. High uncertainty is assigned when the mass of a component is unknown or estimated and multiple material masses are assumed.

Toxicity potential or Material TPI scores are similarly assigned low, medium, or high uncertainty ratings. Material

TPI uncertainty is governed by missing toxicity benchmarks. Low uncertainty is assigned for Material TPI scores where complete information for R-phrases, WGK values, and MAK values/EU carcinogenicity classification are available. Low uncertainty TPI ratings can also occur when a zero Material TPI is calculated due to unavailable toxicity information and a comprehensive literature search indicates no human health or ecological toxicity. Medium TPI uncertainty is assigned when there are 2 input parameters missing. Medium uncertainty TPI scores are also assigned when material toxicity information used in the TPI calculation are derived from a surrogate form of the actual material (due to a lack of available data). High uncertainty is assigned when there is no toxicity information available.

By using these definitions, we are able to carry out sensitivity analyses to compare with the results generated using our baseline assumptions.

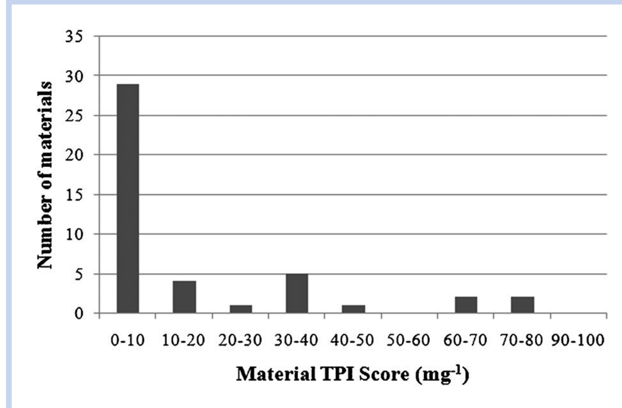

Figure 2. Distribution of Material TPI scores (per mg) associated with substances present within the utility meter products.

RESULTS AND DISCUSSION

Component compositions and Material TPIs

The ranking by mass of components within the PulsePoint is shown in Figure 1. This chart also shows the relative mass contribution based on material category: metal, polymer, ceramic, and other (that includes glass, liquid crystals, magnets, and plasticizers). The vertical scale is reported in terms of the percent mass of a component relative to the product's total mass. Equivalent figures are provided in the Supplemental Data for the other products analyzed (Figures S2–S4).

Material TPI scores are calculated for all materials identified within product components using available toxicity information. The materials composition and associated Material TPI scores are provided in detail in Table S1 of the Supplemental Data. The histogram in Figure 2 summarizes the distribution in Material TPI scores for all of the materials within the 4 products. The majority of the materials have scores between zero and 10 TPI per mg, and the rest are nonuniformly distributed.

For polymers, acrylonitrile-based materials, such as acrylonitrile butadiene styrene (ABS) and buna-N nitrile rubber, and also PVC are responsible for some of the highest toxicity potentials with Material TPI scores of 79.5 and 39.4 per mg, respectively. Acrylonitrile-based polymers are used in shell and grommet components in the products. PVC is used in components such as RotaRead's housing and various products' cable wire. Both acrylonitrile and vinyl chloride exhibit carcinogenic potential to humans (WHO 1999, 2008). For metal and metal alloys, stainless steel is highlighted for its toxicity potential. Stainless steel's main toxicity concern is attributed to Ni and Cr with Material TPI scores of 38.0 and 66.9 per mg, respectively. Ni and Cr (which can be transformed into hexavalent Cr in fumes during stainless steel processing) are both known carcinogens (Sjögren et al. 1994; WHO 1997). Stainless steel is used in components such as the brackets and housing for the PulsePoint and RegistRead, respectively. In addition, metallic lead (Pb) also has a high Material TPI score of 63.4 per mg. Lead is a well-known hazard, and is currently restricted in use by the EU RoHS Directive (Restriction of the Use of Certain Hazardous Substances) due to its environmental and health concerns (EC 2003). It is used minimally within the utility meter products, but is present in solder material for the PWB and within assorted PWB components such as resistors, capacitors, and transistors.

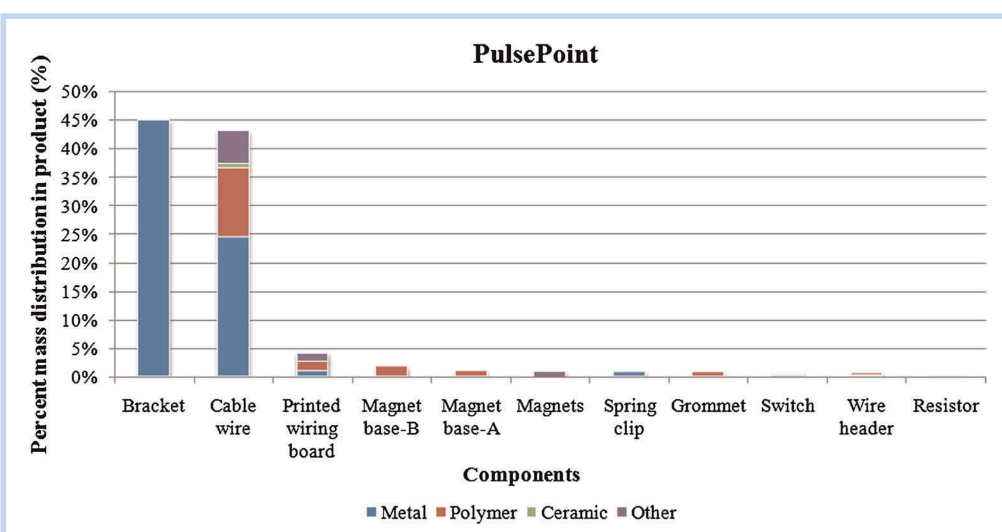

Figure 1. PulsePoint material mass compositions. Equivalent results for the RotaRead, RegistRead, and RCD units are provided in the Supplemental Data.

Component TPI analysis

From estimates of the mass of materials in each component and calculated Material TPI scores, both the Sum-weighted Component TPI and Max Component TPI methods are implemented to identify high priority components for alternatives assessment. Figure 3A illustrates the prioritization of components using the Sum-weighted method for the PulsePoint. Equivalent results for the other products are provided in the Supplemental Data. These Sum-weighted Component TPI results are displayed as a percent of the total Component TPI scores for the entire product unit.

With the Sum-weighted Component TPI method, components with significant mass contributions in stainless steel and acrylonitrile- and PVC-based polymers consistently demonstrate the highest toxicity potential for the utility meter products. High priority components containing stainless steel include the PulsePoint's bracket and RegistRead's housing components. Highlighted components due to acrylonitrile- and PVC-based polymers include the RegistRead's shell; the PulsePoint, RegistRead, and RotaRead's cable wires; RotaRead's housing; and the PulsePoint and RegistRead's grommet components. The RCD unit's enclosure case component, containing polycarbonate material (deriving from bisphenol A's toxicity data), and its Li ion battery exhibit the highest toxicity potentials for this product.

As a second analysis approach, results for the Max Component TPI method are presented in Table 1 for the top 5 priority components for all 4 products. The contributing high toxicity potential materials are noted in parentheses. The high priority components, again, contain acrylonitrile- and PVC-based polymers, and stainless steel and Pb for metals. Note that the Max Component TPI method de-emphasizes some of the higher mass components on the priority list because mass quantities are not considered. A clear example of this is the RCD unit's enclosure case and Li ion battery, which, despite being highlighted in the Sum-weighted method, do not show up in the Max Component TPI top 5 list. They are displaced by other lower mass components containing acrylonitrile-based polymers and Pb.

The Sum-weighted and Max Component TPI methods prioritize some of the same components but they also lead to differences. These discrepancies are expected because one method considers mass contribution effects to TPI whereas the other does not. Although we do not explicitly favor one Component TPI analysis method over the other, the Sum-weighted method seems to be more inclusive as it considers both material mass composition and Material TPI scores simultaneously. However, as mentioned, a drawback of this approach during toxicity screening is that low-mass, high-toxicity-potential materials can be overshadowed by high-mass counterparts with lower toxicity potential. This is exemplified with Pb, which, although having a high Material TPI score, is not generally significant in the Sum-weighted Component TPI scores because Pb-containing components contribute minimally to the mass of products.

Sensitivity analysis

In addition to contrasting Sum-weighted versus Max Component TPI results, we further reviewed the robustness of our toxicity potential analysis by assessing the impact on the results due to uncertainty in toxicity and material composition estimates. For this purpose, we considered the sensitivity of component prioritization in the context of the composition and Material TPI uncertainty rubrics (i.e., low, medium, and high) described previously. These detailed uncertainty designations are provided within Table S1 in the Supplemental Data.

Although other variations are possible, the sensitivity analysis used in this study assumed a type of worst-case scenario for uncertainty and is conducted as follows

1. High uncertainty Material TPI scores are adjusted with these criteria:

   (a) If WGK is not available, change hazard class from nonhazardous to very hazardous in water for TPI calculations.

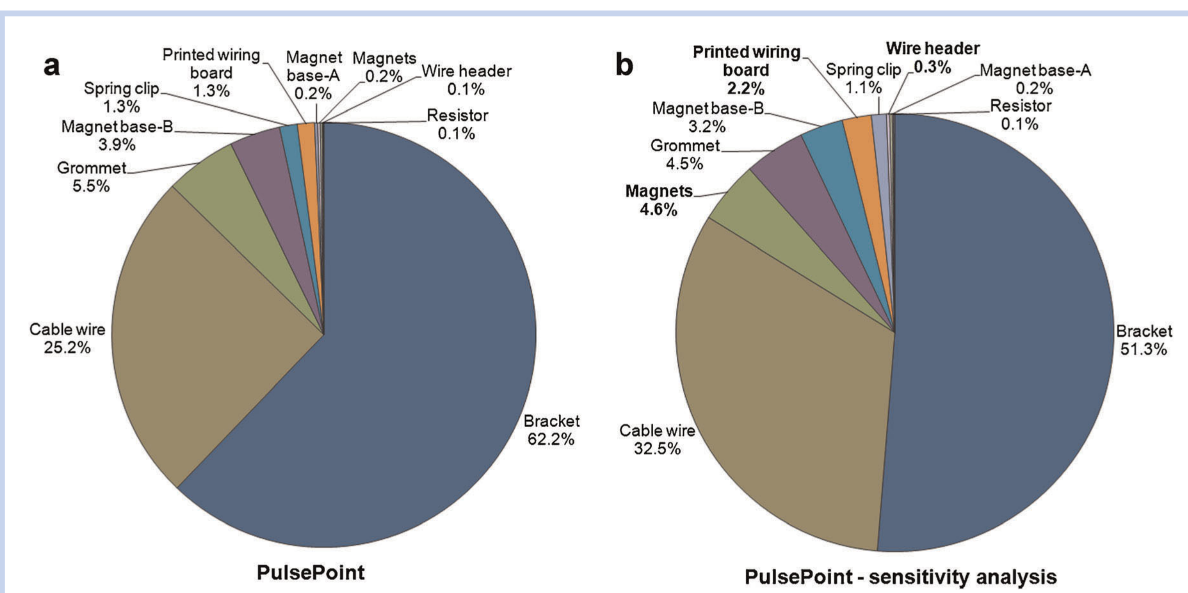

Figure 3. Prioritization of PulsePoint components on the basis of the (A) baseline and (B) sensitivity analysis results with the Sum-weighted Component TPI method. Equivalent results for the RotaRead, RegistRead, and RCD units are provided in the Supplemental Data.

Table 1. Prioritization of components on the basis of the max component TPI method and their associated high toxicity potential materials marked in parentheses

Rank	PulsePoint	RegistRead	RotaRead	Remote consumption display
1	Grommet (Buna-N nitrile rubber)	Grommet (Buna-N nitrile rubber)	Shell (ABS)	Grommet (Buna-N nitrile rubber)
2	Bracket (Stainless steel)	Shell (ABS)	Printed wiring board (Pb)	Phone jack (ABS)
3	Spring clip (Stainless steel)	Housing (Stainless steel)	Resistor (Pb)	Assorted PWB components (Pb)
4	Printed wiring board (Pb)	Printed wiring board (Pb)	Housing (PVC)	Assorted PWB components (Pb)
5	Resistor (Pb)	Resistor (Pb)	Cable wire (PVC)	Assorted PWB components (Pb)

ABS = acrylonitrile butadiene styrene; Pb = metallic lead; PVC = polyvinyl chloride; TPI = Toxic Potential Indicator.

(b) If a MAK value is not available, instead of using a zero value, use occupational exposure limits published by the American Conference of Governmental Industrial Hygienists (ACGIH 2009). If these limits are not available, use highest EU Carcinogenicity classification of 1 (definition: "known to be carcinogenic to humans") for MAK considerations.

2. For components with medium or high uncertainty in their composition value, sensitivity analysis is performed by doubling the materials' mass in the component (100% increase).

Material TPI score changes induced by the above criteria include

- Barium titanate (in capacitors) from 0.8 to 67.4 TPI per mg
- Diisodecyl phthalate, dioctyl phthalate, diundecyl phthalates (in plasticizers) from 0.6 to 33.9 TPI per mg
- Indium tin oxide (in the LCD screen) from 1.8 to 37.8 TPI per mg
- Molybdenum disulfide (used as lubricant in the magnetic shaft) from 0.0 to 0.6 TPI per mg
- Kaolin (in potting materials) from 0.0 to 1.2 TPI per mg
- Neodymium (in magnets) from 0.8 to 33.9 TPI per mg

The effect of these Modified Material TPI values on component ranking depends on the Component TPI method applied. For the Max Component TPI method, the prioritization of components is not changed in products, because: 1) these results are not sensitive to effects of materials composition uncertainty, and 2) our sensitivity analysis results show that the materials with Modified Material TPI scores (due to uncertainty in the toxicity information) still have lower values, in general, than the high priority materials previously identified: acrylonitrile- and PVC-based polymers, stainless steel, and Pb. The only exception is for the RCD unit's capacitor component, which is now ranked within the top 5 priority components due to the significant increase in the Modified Material TPI score for Ba titanate.

With the Sum-weighted Component TPI method, many of the prioritized components remain stable (e.g., housings, cable wires, and brackets) when considering uncertainties in input parameters. However, there are some notable shifts. For example, the results for the PulsePoint shown in Figure 3B, indicate that, when compared to the baseline results, the magnets, PWB, and wire header move up in priority (marked in bold). These components shift in priority because of changes in Material TPI or material masses due to sensitivity effects.

Toxicity, technical, and cost considerations of alternatives

To identify possible alternatives for materials with high Component TPI scores, it is first necessary to aggregate the results of the baseline and the sensitivity analyses using the 2 Component TPI methods. Table 2 contains the illustrative example for the PulsePoint, with a summary of the top 5 prioritized components by rank as determined with each of the 4 component analysis scenarios. Equivalent tables are provided in the Supplemental Data (Table S2) for the other products. For the PulsePoint, the bracket and grommet components are in the top 5 regardless of scenario, although their respective ranks are observed to vary. The neodymium magnets move up in rank (now into the top 5) for the sensitivity analysis scenario using the Sum-weighted Component TPI method. As discussed above, there are no shifts due to sensitivity when comparing the 2 scenarios within the Max Component TPI method. It is noted, however, that included in this latter list are PWBs and resistors, which are not part of the top 5 when the Sum-weighted Component TPI method is used.

The data provided in Table 2 and Table S2 for the products are used in conjunction with available data on possible alternative materials, including performance requirements, to select a short-list of components for further investigation to improve product toxicity performance. We ultimately identified the bracket, grommet, housing (both stainless steel and PVC-based) and shell components for alternatives recommendations.

Some components are not selected for alternatives assessment due to limitations such as toxicity, cost, and lack of available technology options. In the case of neodymium

Table 2. The top 5 priority components in the PulsePoint as determined with the sum-weighted and max component TPI methods, with both baseline and sensitivity analysis assumptions

PulsePoint Component Rank	Sum-weighted method (baseline)	Sum-weighted method (sensitivity analysis)	Max method (baseline)	Max method (sensitivity analysis)
1	Bracket	Bracket	Grommet	Grommet
2	Cable wire	Cable wire	Bracket	Bracket
3	Grommet	Magnets	Spring clip	Spring clip
4	Magnet base-B	Grommet	Printed wiring board	Printed wiring board
5	Spring clip	Magnet base-B	Resistor	Resistor

magnets, which moved up in priority due to data uncertainty, alternative rare earth-based materials exhibit equivalent toxicity uncertainty. Although the Pb-based components show high Material TPI, Pb has already been targeted for replacement in response to the EU RoHS Directive and other legislative initiatives. Options for different chemistry Li ion batteries (e.g., Manganese dioxide as opposed to the thionyl chloride chemistry within the RCD unit) are also investigated. However, Material TPI scoring for the different chemistry battery shows no advantage in toxicity potential reduction, making it difficult to recommend a replacement. The NEMA-4 (an outdoor protection rating) enclosure case for the RCD unit has a high Sum-weighted Component TPI score, yet there is currently no similar material option available that provides the same protection rating as the original polycarbonate. Although cable wires consistently show up in the Sum-weighted Component TPI analysis for several of the products because of the PVC insulator material, the challenge of significantly higher cost polyethylene or rubber alternatives (both with lower toxicity potential) prevented the cable wire component from being included in the recommendations list at this time.

In assessing options for the components selected for further study, materials are screened on the basis of their desired technical requirements (e.g., corrosion resistance, ultraviolet light resistance, machinability). In addition, cost is modeled as the raw material price, which is a simplistic but transparent way to assess the economic potential of an alternative material for a given component. Material property and cost information is principally compiled from 2 main sources including MatWeb (MatWeb 2012) and the CES software database. The CES database collects the average cost of raw materials from the London Metal Exchange for metal prices (LME 2012) and Plastics Technology for polymer resin prices (Plastics Technology 2012). Granta, the CES software developer, also provides material cost modeling for alloys, composites, and filled polymers for compound materials.

The details of the technical requirements and recommendations list for the components analyzed are provided in Table 3. Note that there are overlaps in product components on the recommendations list (e.g., the same grommets are used for the RegistRead, PulsePoint, and RCD unit and the same shell for the RotaRead and RegistRead).

As shown in Table 3, Tier 1 and Tier 2 material recommendations are made for the components through screening of potential material substitutions and working with RIO Tronics on understanding technical constraints. Tier 1 would ultimately be the optimum material substitutions based on the listed criteria while considering cost, material requirements, and TPI performance. A Tier 2 recommendation may not perform as well in terms of TPI scoring or cost; however, it is expected to still outperform the original design in toxicity potential and can also be seen as a feasible material option. All suggested alternative materials have low or medium uncertainty ratings associated with their Material TPI scores.

Aluminum-based materials are benchmarked as a good alternative to the stainless steel components such as PulsePoint's bracket and RegistRead's housing due to lower toxicity potential. However, with the exception of Al 3003, Al grades that possess superior corrosion resistance have trace Cr additives, which contribute slightly to their toxicity potential. High-density polyethylene (HDPE) and polypropylene are seen as good alternatives to the ABS and PVC-based polymer components due to their lower Material TPI scores. Ethylene-propylene copolymer rubber is recommended as a substitute for buna-N nitrile rubber in grommets.

A summary comparison of the relative Material TPI scores and cost (in terms of percent reduction as compared to the original) for available Tier 1 and Tier 2 material recommendations is shown in Figure 4. In general, alternatives show excellent cost-effectiveness with the price of Tier 1 materials also outperforming that of the original raw material. Several Tier 1 material alternatives show that a combination of toxicity reduction and lower material cost can be achieved within various components. Although Tier 2 material substitutions still retain positive toxicity potential reduction, they can represent increased cost relative to original materials. These findings are indicated by negative values for cost percent reductions as illustrated for the grommet, shell and PVC housing components.

Caveats on toxicity screening for products

Challenges remain in the materials and component screening for products. An important aspect of product DfE, as illustrated in this study on utility meter products, is the need to have a good estimate of the materials composition of the product components analyzed. Most manufacturers do not provide motivation to upstream suppliers to disclose materials used in their components. In other instances, proprietary conflicts hinder full material composition disclosure, making the correct identification of hazardous materials and their quantities for toxicity screening very challenging. Encouragement of material

Table 3. Technical requirements and alternative materials recommendations for select components

Component	Product	High TPI material	Component technical requirements	Alternatives Tier 1	Alternatives Tier 2
Metal-based components					
Bracket	PulsePoint	304 Stainless steel	Corrosion resistant Nonmagnetic Machinable	(a) Al 3003	Al 5052
Housing	RegistRead	304 Stainless steel	Corrosion resistant Nonmagnetic Ultraviolet light resistant Water resistant	(a) Al 3003	Al 5052
Polymer-based components					
Grommet	PulsePoint RegistRead RCD unit	Buna-N nitrile rubber	Nonmagnetic Water resistant UV light resistant	(a) Ethylene-propylene copolymer	Silicone (polysiloxane)
Housing	RotaRead	PVC	UV light resistant Water resistant Machinable	(a) HDPE (b) Polypropylene	Nylon 6
Shell	RegistRead RotaRead	ABS	Electric insulation Acceptable polymer shrink rate for molding Drillable Adhesion to potting materials	(a) HDPE (b) Polypropylene	Nylon 6

ABS = acrylonitrile butadiene styrene; HDPE = High density polyethylene; PVC = polyvinyl chloride; RCD = Remote Consumption Display; TPI = Toxic Potential Indicator; UV = ultraviolet.

disclosure in the supply chain can occur when companies require this information to conduct business. On the regulatory front, material disclosure requirements to the government are already occurring in the EU as companies are mandated to register potentially hazardous chemicals being used or produced in compliance with the Registration, Evaluation, Authorization and Restriction of Chemicals legislation (REACH 2006).

In terms of toxicity screening, future work should focus on making available and standardizing toxicity information for use in these assessments. This is especially important for polymers, alloys and compound materials. Toxicity benchmarks for polymers and alloys are often missing entirely in public databases. Results with this more conservative approach can sometimes be counterintuitive. High toxicity potential materials highlighted in this study such as ABS plastic or stainless steel are used ubiquitously in many consumer applications (e.g., cookware or utensils for stainless steel) with low toxicity concerns during use. However, these materials are highlighted in this hazard-based approach because of their potentially carcinogenic constituents (e.g., acrylonitrile, Ni, and Cr), which implies that these materials should be removed from products if at all possible because of their potential impact on human health or the environment through other exposure routes or transformation products. It is acknowledged here, however, that for these utility meter products these substances may or may not represent a real exposure concern. Furthermore, because the upstream manufacturing or long-term downstream degradation behavior of these materials in the environment is unknown, it is also possible that significant ecological and human health impacts may not be accounted for in this type of hazard assessment. For example, the environmental fate and possible transformation of metals into other forms from their constituents are difficult to ascertain. Also, other dimensions such as life cycle energy use or environmental impacts attributed to materials extraction and processing are not directly captured and would be beyond the scope of hazard-based screening. In addition, material recovery potential, such as for metal alloys and various plastic grades, are separate aspects of product design that can influence a product's recyclability (Choi et al. 2006), and therefore contribute to the final selection of materials and components. However, for comparative evaluation and subsequent redesign of complex, multicomponent products, hazard-based assessment provides a valuable decision support tool to facilitate the elimination of toxics in products.

CONCLUSIONS

This research provides justification for standardizing methods and data for toxicity screening during materials and component selection. This includes integration of a simple method, as exemplified by the TPI method, which allows for quantitative assessment of different types of materials. Product manufacturers and engineers can use this approach to develop a preliminary comparison of the toxicity potential of product components in much the same way they compare traditional functionality requirements. In addition, uncertainty must be reflected in some format to denote the reliability of toxicity and materials composition information used to assess the toxicity profiles. The research presented in this article illustrates how Material TPI scoring is used to address such issues to help guide materials selection for the redesign of utility meter products. Such methods can be extended to other alternative assessments to effectively help manufacturers benchmark the toxicity

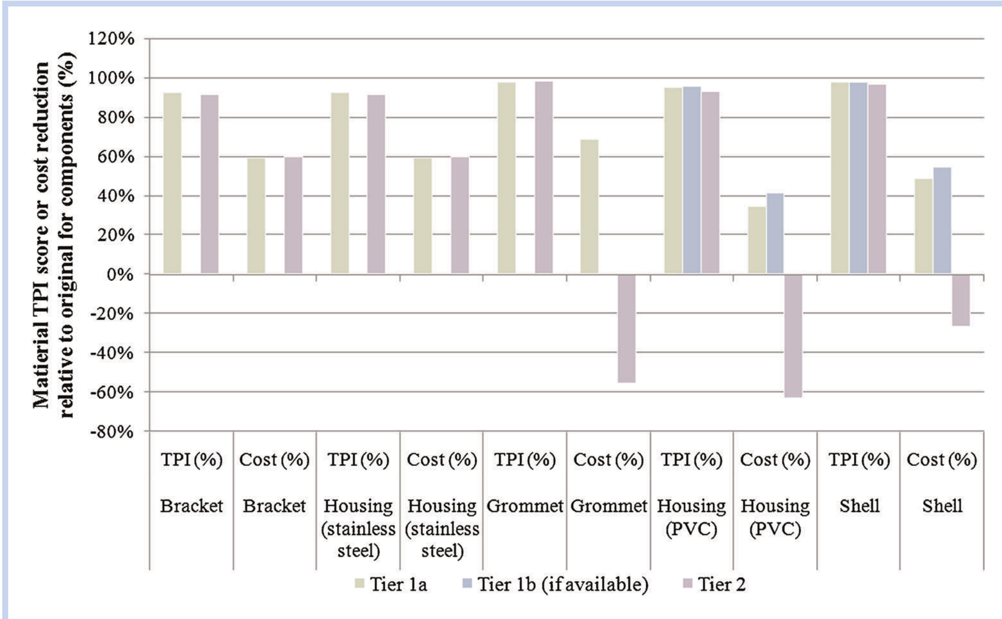

Figure 4. Percent reductions in Material TPI score and cost for alternative materials (Tier 1 and Tier 2) relative to values for the original materials in select components. Component, product affiliations: bracket, PulsePoint; housing (stainless steel), RegistRead; grommet, PulsePoint, RegistRead, RCD unit; housing (PVC), RotaRead; shell, RegistRead, RotaRead.

potential of components used in other types of products while considering factors such as cost and technical performance.

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SUPPLEMENTAL DATA

Details on the materials, methods, and quantitative results.

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