UNIVERSITY OF CALIFORNIA

Santa Barbara

Improving the Usefulness of Environmental Information for Decision Making in Organizations

A dissertation submitted in partial satisfaction of the

requirements for the degree Doctor of Philosophy

in Environmental Science & Management

by

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December 2018

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By

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PUBLICATIONS

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Patton A.P., Perkins J., Zamore W., Levy J.I., Brugge D. & Durant J.L. 2014. Spatial and temporal differences in traffic-related air pollution in three urban neighborhoods near an interstate highway. *Atmospheric Environment*, 99: 309-321.

DiMuro, J. Guertin, F.M., Helling, R.K., Perkins J.L. & Romer, S. 2014. A Financial and Environmental Analysis of Constructed Wetlands for Industrial Waste Water Treatment. *Journal of Industrial Ecology*, 18: 631-640.

Perkins, J. & Suh, S. 2018. Uncertainty implications of hybrid approach in LCA: precision versus accuracy. *Environmental Science & Technology*, submitted December 2018.

Callery P. & Perkins, J. 2018. Intermediated Voluntary Disclosure: Stakeholder Sword or Corporate Shield? *Academy of Management Discoveries,* submitted November 2018.

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ABSTRACT

Improving the Usefulness of Environmental Information for Decision Making in Organizations

by

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With the growing attention to environmental issues, knowledge in the environmental and sustainability sciences is increasingly needed to inform decision making in policy, industry and at the consumer level. At the same time, the tools and communication strategies produced by this scientific community have been criticized for their lack of practicability and usefulness. Many questions remain about the mechanisms that create these knowledge transfer barriers and the avenues that should be explored to find solutions. The following work analyzes three different case studies where environmental information has been criticized for its limited usefulness. The theoretical background and research methodologies used throughout the chapters draw from several disciplines across both the natural and social sciences: industrial ecology, life cycle assessment, organizational science, management science, communication studies, and behavioral psychology.

Chapter one considers the usefulness of life cycle assessment (LCA) results in aiding product developers and businesses in drawing comparisons and identifying hotspots of environmental impacts. LCA has been broadly criticized for both the degree of uncertainty introduced through data gaps and the use of input parameters of variable quality. This work evaluates the tension between improving the accuracy of LCA results by filling in data gaps and decreasing the precision by incorporating less certain inputs. Through a real-world case

study, the uncertainty implications of the hybrid LCA approach is analyzed in this context of accuracy versus precision. For firms to manage the environmental impacts of their value chains, they first must be able to quantify those impacts. This study presents an iterative hybrid approach to LCA that allows industry LCA practitioners to efficiently identify which parameters are most critical to understand the impacts, facilitating an efficient data collection process and an improvement to both the accuracy and precision of the quantified impacts used to support decision-making.

Chapter two focuses on an organization's internal knowledge about chemical risks in consumer products and the mechanisms that prevent this information from being used to educate the public. Companies are taking proactive approaches to mitigating the risks of chemicals in their products, but new chemical risk identifications and removals are done quietly and rarely promoted to the public. Through an experimental survey design this study analyzes how consumer behavior is affected by a company's voluntary disclosure of these proactive actions, and special attention is payed to the influence of media on the consumer response in these scenarios. This work examines the mechanisms that drive consumer response and the incentive that consumer behavior creates for companies to stay silent. Consumer trust in the information source helps to explain why the same information can be interpreted and acted upon very differently depending on where the information is coming from. Understanding the negative implications of voluntarily disclosing these positive actions offers insights into how creative solutions, such as disclosure through information intermediaries or third-party certifications, might be necessary for firms to retain consumers' trust.

The last chapter focuses on the challenge of integrating knowledge generated within an organization's sustainability function throughout an entire organization. Sustainability is an increasingly adopted practice within present-day organizations; however, very little research has empirically studied the micro-level process through which it is implemented and adopted by employees. Research on the decoupling of policy from practice in management programs – often brought on by external pressures – sheds light on the initial adoption of sustainability within organizations. This work examines individual employee behavior and the different motivations that may drive ceremonial adoption of sustainability versus actual integration of knowledge and practices. A survey completed by 886 employees within a Fortune 500 consumer goods manufacturing company based in the United States was used to measure employee characteristics, attitudes and both formal and technical sustainability-related behaviors. Employees' perceptions of the business value of sustainability and their own personal sustainability interests may act as drivers of sustainability adoption throughout the organization. This study examines the relationship between these potential drivers and the prevalence of sustainability communication and information seeking behavior. This work offers insights into how management strategies can be employed to increase the technical adoption of sustainability, not just the expansion of a formal rhetoric.

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Chapter One: *Uncertainty implications of hybrid approach in LCA: precision versus accuracy*

Introduction

Process life cycle assessment (LCA) has been the dominant approach in LCA.[1-3] Among the thirty most cited LCA studies according to the Thomson Reuter's Web of Science published since 2010, only two used the input-output (IO) approach, two used the hybrid approach, and the rest employed the process LCA approach (see Table 1s; a full list can be found in the SI).

Despite the dominance of process LCA, it has been repeatedly pointed out that process LCA approach may suffer from truncation error and underestimate LCA results.[4-8] Truncation error refers to "the proportion of impact not covered by the system boundary of the LCA",[2] which can occur when flows are knowingly ignored, as well as when relevant data are (unknowingly) missing or disregarded.

Previous research indicated that truncation error varies widely across sectors[12] and that modelling and methodological factors significantly influence the estimated magnitude of truncation error. Lave and colleagues (1995), for example, used a paper cup example to show that with a process LCA approach less than half of the environmental discharges are accounted for, then demonstrated the usefulness of IO analysis to address this issue.[6] Treloar analyzed truncation error (1997) in the Australian residential building sector, demonstrating that the energy intensity of the processes one, two and three stages upstream were 40.9%, 27.1%, and 7.61% respectively (12.4% were the building's direct emissions), shedding more light on the potential significance of cutoff and system boundary decisions.[7] Lenzen (2001) further investigated truncation error in a broader range of applications, demonstrating that across sectors and product types truncation error was estimated at 50% in process LCA studies.[8] Ward and his colleagues (2017) reported a range of 30-80% truncation error across their modeling scenarios.[2]

These estimates of truncation errors are the result of simulations mostly using input-output tables as a proxy. In reality, the magnitude of truncation error in a given LCA can hardly be measured in an empirical setting, because no data is collected for truncated flows, and thus their contribution to the overall LCA result is unknown; if they are known, there is no reason to truncate them.[9-11] Furthermore, cut-off decisions are made often inconsistently across LCA studies, making the effort to standardize the procedure of measuring truncation error a challenge.[2]

The hybrid LCA approach has been recommended in the literature as a means to reduce truncation error of process LCA or to improve precision of input-output analysis.[2,13-15] Questions still remain about the overall uncertainty implications of adding IO data to a process LCA using the hybrid LCA approach. Recently, two publications have drawn opposite conclusions about the implications of the hybrid LCA approach on the accuracy of LCA study results.[50,51] Input-output LCA data may show higher variability due to sector aggregation and temporal system boundaries[9,16] and the propagation of such uncertainty in a hybrid LCA study is not well understood. This paper attempts to elucidate the implications of hybridization on uncertainty through the lens of precision and accuracy.

Precision and accuracy were explicitly defined in the ISO standard 5725-1 (Accuracy (trueness and precision) of measurement methods and results - Part 1: General principles and definitions).[32] Accuracy is "the closeness of agreement between a test result and the accepted reference value", or rather the closeness of a measurement to the true value.[32] Precision is "the closeness of agreement between independent test results obtained under stipulated conditions", or the closeness of agreement among a set of results.[32] Brandão and colleagues used the distinction to characterize consequential (more accurate) and attributional (more precise) LCAs.[37] Of the many categories of uncertainty previously described in the LCA literature (also included in the Supplemental Information), several are able to partially represent the accuracy and precision dimensions of uncertainty; however, none holistically address or explicitly call out either metric. The review of the most cited LCA case studies presented in Table 1s indicates that fewer studies address uncertainty topics related to accuracy (truncation error) than did precision (parameter uncertainty, model uncertainty, aggregation).

One of the reasons for underrepresentation of accuracy aspects in LCA is that accuracy is more difficult, if not impossible, to measure in the LCA context; in order to quantify accuracy, one needs to know the true value, which is generally not known in the context of LCA. In that sense, accuracy cannot be quantified or proven in a scientifically defensible way in the LCA context, but may only be inferred by means of the convergence as we know the entire product system better. In the LCA literature, proxy measures such as completeness of system boundary definition and comparisons between IO or hybrid LCA results and process LCAs have been used instead to address accuracy.[2]

The objective of this paper is to (1) compare the uncertainty results for a process LCA to that using the hybrid LCA approach and (2) use sensitivity analysis to iteratively refine the hybrid LCA results to improve the overall precision and accuracy.

Methodology and Data

Study Design

Our study was conducted in three steps: (a) Select a process LCA case study and run Monte Carlo simulation (MCS) with all available process data and parametric uncertainty characterization, (b) hybridize the LCA study by filling in data gaps with IO data and run MCS after the addition of data to each process, and (c) identify the top contributors to uncertainty and reduce the parametric uncertainty values of these highest contributors to simulate further data collection and refining of the LCA, and again run MCS after the refinement of each process. Each of the three steps is described in its own subsection below. This approach aligns well with the recommendation from the literature to employ an iterative process for the use of the hybrid LCA methodology with assessment of uncertainty.[9-10,53] The iterative approach leads to a gradual refinement and highlights the optimized improvement of the overall study results when refinement is used in combination with the hybrid LCA approach. Each MCS included 1,000 runs, varying each parameter randomly within the lognormal distribution of values possible based on its geometric standard deviation (GSD). A GSD describes how spread out the numbers are in a set that's preferred average is the geometric mean, and GSDs are commonly used to characterize uncertainty in LCA databases (including ecoinvent and CEDA) where a significant portion of LCA process data are lognormally distributed. The uncertainty of the results at each of the three steps (a,b,c) was interpreted in the context of both precision (standard deviation of the MCS results) and accuracy (evidence of reduced truncation error). The following sections describe each of the three steps and high-level overview of the mathematical computations involved. A more comprehensive explanation of the data utilized and mathematical analysis (matrices, Matlab code, etc.) has been included in the Supplemental Information.

(a) Case Study Selection and Process LCA Reconstruction

Several criteria were used to select the case study for this analysis: (1) the example needed to be from the "real world", not purely hypothetical, (2) the product needed to have a complex supply chain that required a laborious data collection effort, and (3) the "complete" set of unit processes in the process LCA needed to be published. A study published by the Mistra Future Fashion Consortium, titled "Environmental assessment of Swedish fashion consumption", was selected.[39] This study, commissioned by Mistra Future Fashion, analyzed five generic Swedish garments, and the jacket was chosen for our analysis due to its material and supply chain complexity in comparison to the others.

The Mistra Future Fashion study had several goals, including assessment of potential consequences of proposed interventions in future scenarios;[39] however, in our study we focus on one aspects of the study's goal: to map the baseline environmental impact of one use of an average jacket. Unit processes and material flows, 193 in total, were provided by the Mistra study's author and used to generate the process flow diagram for the life cycle of a jacket.

Ecoinvent was employed as the primary source of background data LCI in the Mistra study, but one specific version of the database was not used consistently throughout. For the purpose of this study we use ecoinvent v3.1 (more details on data sources are described below). The Mistra study includes ten different impact categories with characterization methods used according to the ILCD guidelines. Of the impact categories they included, we selected the climate change measured in Global Warming Potential 100 (GWP_{100} in $kgCO_2eq$) as the example for our analysis. In the Mistra study sensitivity analysis is used to consider different scenarios that may significantly influence the over results, such as different use phase scenarios (i.e. washing at different frequencies). Aside from scenario uncertainty, no other uncertainty was assessed or characterized in the Mistra study. The study is reasonably complete and well documented, but uncertainty was not quantified. We use the jacket from the Mistra study as the case study for our analysis to shed light on the usefulness of uncertainty assessment to understand the likeliness of outcomes and how system boundary decisions influence the overall results.

Figure 1 displays a high-level process flow diagram for the life cycle of the jacket, modeled directly after the Mistra study report.[39] In reality, there were 193 processes included in both the Mistra study and in the process-based LCA and subsequent uncertainty analysis in step (a) of our study. The processes and individual impact contributions for the process-based LCA are listed in Table 5S in the Supplemental Information. Many of the Mistra study defined processes included are aggregate processes (also referred to as system processes or rolled-up processes) that connect a series of other unit processes but do not have direct impacts themselves, such as the process "weaving" which draws together "production of electricity mix", "production of modified starch" and "disposal, textile", and which itself flows into the larger processes of "production of woven polyamide" and "production of woven polyester". This process is a good example of one that omits processes such as "warehousing and storage" and "business support services" that are typically considered to be negligible in process LCAs.

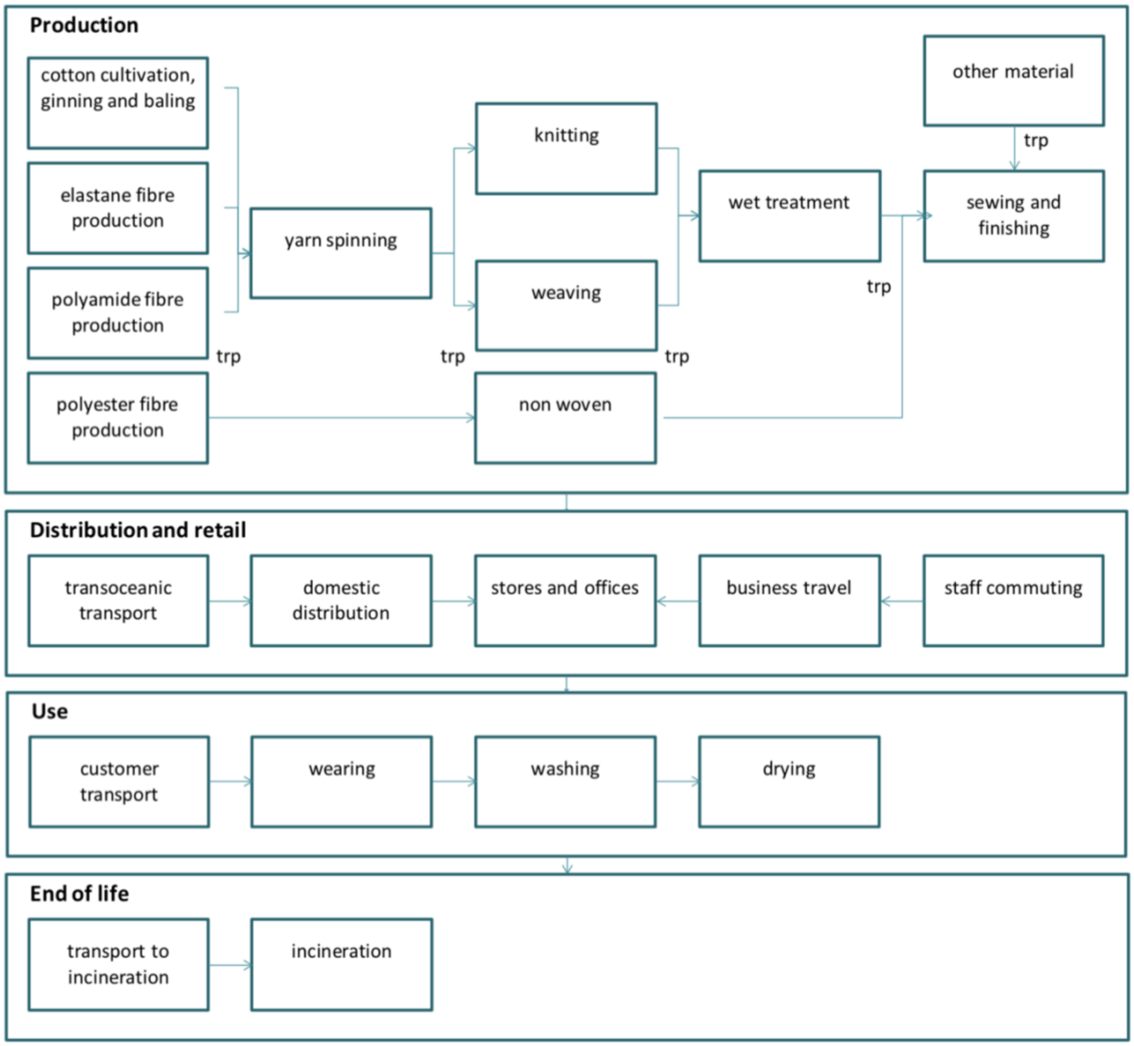

Figure 1. High-level process flow diagram for the life-cycle of a jacket (figure reference: Roos et al 2015[39])

Using the process LCA approach, the technology matrix (A) and environmental exchange matrix (B) were generated based on the processes and emissions reported in the Mistra study. After compiling all of the jacket's unit processes from the Mistra study, the authors used the ecoinvent v3.1 dataset to gather reported upstream process data. A_p^u was generated with the subset of the Mistra study's upstream unit processes that were available in ecoinvent v3.1, and these processes were linked to the full technology matrix in ecoinvent v3.1 (A_p) and the corresponding environmental exchanges matrix (B_p), as noted in equation (1). The total life-cycle impact calculated in step (a), $LCIA_p$, is then given by

$$LCIA_P = [C]\,[B \quad B_p] \begin{bmatrix} I - A & 0 \\ A_p^u & I - A_p \end{bmatrix}^{-1} \begin{bmatrix} y \\ 0 \end{bmatrix}, \qquad (1)$$

where y represents the functional unit in the Mistra study (use of one jacket) and the C matrix includes the characterization factors to transform the emissions associated with the life cycle inventory into life cycle impacts based on the TRACI methodology (GWP_{100} measured in $kgCO_2eq$). The original matrix notation that the ecoinvent database follows A^{-1} form for the total direct and indirect requirements as presented in Heijungs and Suh (2002), [42] instead of $(I - A)^{-1}$ form used here. In this paper, however, we follow $(I - A)^{-1}$ form for the sake of consistency with the input-output literature.

The uncertainty characterization values (GSDs) were extracted from the ecoinvent v3.1 database, and a Monte Carlo simulation was performed by randomly varying each parameter based on its distribution, ultimately generating 1,000 results for $LCIA_P$. The mean, median and standard deviation of these 1,000 results were calculated as a means of measuring the precision of the result. The values in the technology matrix (A), environmental exchange matrix (B), and upstream cut-off matrix (A_p^u) did not accompany GSDs, and we assumed that their GSD is 1. We recognize that overall uncertainty estimates are likely underestimated without accounting for the variation in these matrices.

(b) Hybridization process

In this study, we used the tiered hybrid LCA approach to hybridize the Mistra case study,[40,41] first identifying the upstream processes that may have been excluded during boundary selection. The authors of the Mistra study reported the omission of certain upstream processes that are commonly excluded from process LCA calculations: "Generally, manufacturing of machinery and equipment are not included in the models unless there has been a specific reason for doing so."[39] LCA databases, such as ecoinvent, however, aim to incorporate capital goods including machinery and equipment within the system boundary, while the degree of success may vary widely across unit processes and databases.

To determine the magnitude of these and similar processes that are typically excluded, the direct economic flows into the sectors relevant for the jacket's production were analyzed using the CEDA 5 input-output LCA database. Five sectors were considered in the analysis to be directly relevant to the jacket's upstream production: (1) fiber, yarn, and thread mills, (2) fabric mills, (3) textile and fabric finishing and fabric coating mills, (4) other textile product mills, and (5) apparel manufacturing. Analyzing only inputs into these five sectors, the average contribution of each commodity was determined, and the contributions were ranked. Only the inputs contributing at least 0.1% of the total cost to produce each output of the five jacket-related sectors were included in the hybridization, and the sectors that overlapped with the process LCA data used in step (a) were excluded. For example, the contribution of the "fabric mills" commodity was not included in the hybridization, since several fiber production processes were already included in the Mistra study's LCA; however, the "management of companies and enterprises" commodity was not already included in the process LCA and so was added using input-output data during the hybridization. Table 3S in the supplemental information contains the list of sectors identified during the aforementioned analysis and those included in the hybridization process (36 in total).

After establishing the baseline process LCA scenario and results in step (a), the additional upstream processes identified from analyzing the jacket-related sectors in the CEDA database were added through the integrated hybrid approach[13]. However, as discussed in Suh and Huppes (2005), integrated hybrid approach and tiered hybrid approach[40] would, in this particular case, generate identical results, as there is no feedback loops between the input-output and process systems through downstream cut-off matrix[38,52]. The price of the jacket, estimated at $40 USD, was used to quantify the size of the contribution of each upstream process, since the contribution of each commodity per USD jacket production was previously determined. The magnitude for each of these commodities were modeled as upstream processes in the C_{IO}^{u} matrix, and then linked to the CEDA technology matrix data (A_{IO}) and environmental exchanges data (B_{IO}) using the hybrid approach.

Using the tiered hybrid approach, both the processes using process-based data and those using input-output data were modelled as upstream processes (A_p^u and C_{IO}^u, respectively) to distinguish between the two data sets (both matrices are included in the Supplemental Information). The overall computation using the tiered hybrid approach is given by

$$LCIA_H = [C]\,[B \quad B_p \quad B_{IO}] \begin{bmatrix} I - A & 0 & 0 \\ A_p^u & I - A_p & 0 \\ C_{IO}^u & 0 & I - A_{IO} \end{bmatrix}^{-1} \begin{bmatrix} y \\ 0 \\ 0 \end{bmatrix}, \quad (2)$$

which represents the total life cycle impacts generated by the jacket in scenario (b) of our study.[40-41] The uncertainty distributions for the contribution of each commodities to the jacket-related sectors (standard deviation of the average of all five sectors) and the CEDA data inputs (GSDs) are used, along with the uncertainty information for the environmental exchanges from ecoinvent (GSDs), to vary parameters during the Monte Carlo simulations. Just as in step (a) the mean, median and standard deviation of these 1,000 results were calculated for comparison.

(c) Iterative Refinement of Hybrid LCA Results

Progressive replacement of more uncertain, secondary datasets by less uncertain primary datasets was simulated in two steps: (1) identification of the major uncertainty contributors, and (2) simulating the effects of replacing those major uncertainty contributors by primary data. First, in order to identify the major uncertainty contributors, a local sensitivity analysis was performed to identify the contribution of each upstream process (from both process-based and IO data sources) to the overall uncertainty of the results. Monte Carlo simulations were run by varying all of the parameters associated with one process and calculating the standard deviation of the results when only the uncertainty of that process was included. This exercise was repeated for all of the processes and the standard deviations of the results (100 simulations each) were compared. The use of IO data, which is holistic in nature, using the hybrid approach, is currently the only streamlined approach to LCA that addresses the truncation error prevalent in all process LCAs. The focus of this paper is on the implications of the hybrid approach for uncertainty, and the authors recognize that there are several available methods to optimize refinement of the results once truncation error has been properly addressed. These alternatives include the sensitivity analysis method based on first-order approximation discussed in Heijungs and Suh (2002)[42] or the probabilistic triage method presented in Olivetti et al (2013)[53], both of which could be complementary to the methods presented in this paper. The sensitivity analysis results are included in the Supplemental Information (Table 4S), and the calculated uncertainty distributions for each process were used to rank the processes based on their contributions to overall uncertainty of the LCIA results. Second, progressive collection of primary data for and replacement of those top uncertainty contributors was simulated by running a Monte Carlo simulation with 1,000 runs (same as with steps (a) and (b)) using equation (2) each time a process was refined by eliminating the parametric uncertainty associated with that one parameter, simulating the collection of primary data to fill in the data gap. A new Monte Carlo simulation was run each time a new process was refined, and the processes determined to be the highest contributors to uncertainty were refined one-by-one in the rank order described above. The mean, median and standard deviation of each of these Monte Carlo simulation results were calculated to measure how the precision of the results changed with each refinement.

Data Sources

The appendices of the Mistra study included tables with all of the processes utilized and flows between processes for the jacket (on pages 90 – 132). This data was manually extracted from the report, as it was in PDF form, and replicated in an excel spreadsheet format. After determining that our initial results did not match that of the Mistra study, we contacted the authors and they provided a more complete set of unit processes and material flows, which is now incorporated into our case study. The Supplemental Information (SI) of our study includes this more complete set of data in the “A_mistra” matrix in the excel workbook. This workbook in the SI describes in detail what ecoinvent and CEDA data were utilized as well as the background calculations. It is notable that our reconstruction of the Mistra study for the global warming potential of the jacket did not reproduce the exact same result that the original report presented; however, this 7% difference may be attributed to the use of only ecoinvent v3.1 in our study (as opposed to drawing from several ecoinvent versions) and the TRACI method for characterization instead of the ILCD guidelines used in the Mistra study's calculations.

The ecoinvent v3.1 database is used as the primary source of process-based LCI data in this study. Ecoinvent v3.1 contains over 11,000 unit processes, and uncertainty information in the form of distribution of parameters is provided for each unit process data.[43] The distribution of parameters in the ecoinvent database are derived from an estimate of basic uncertainty (stochasticity) and several other criteria incorporated through a pedigree matrix approach, which translates reliability, completeness, temporal correlation, geographic correlation, and further technology correlation into a distribution.[44] The information on distribution of the underlying parameters at a unit process level can be used to simulate the overall distribution in the LCA results.[45]

The pedigree approach has been developed to incorporate both quantitative and qualitative dimensions of uncertainty into one numeric indicator of uncertainty.[46] The pedigree approach has been criticized for its subjectivity and reliance on expert judgement;[47] however, viable alternatives to incorporate the inherent uncertainties in LCA is lacking. The Comprehensive Environmental Data Archive (CEDA) database is the source of all input-output data used in this study.[48] CEDA 5 represents over 430 industrial sectors, commodities, and the linkages between them according to a 2014 base year. GSD values for individual parameters in CEDA are derived from the same pedigree approach used to estimate uncertainty for the parameters in ecoinvent to ensure comparability. In general, GSD values in CEDA are higher than those in ecoinvent due to the uncertainty caused by aggregation error. The median GSD in ecoinvent v3.1 is 1.2 while that for CEDA 5 is 1.8. Despite the fact that CEDA GSDs are generally higher than that of ecoinvent, the median GSDs for CEDA and ecoinvent data utilized in our analysis were quite similar (median GSD from CEDA = 1.3, median GSD from ecoinvent = 1.4). This is likely because the ecoinvent data in this study was utilized for the more complex processes, such as the production of various chemicals, while CEDA data was used for many processes that predominantly required energy consumption, such as warehousing and business services. While the median GSDs were comparable, Figure 2 demonstrates that ecoinvent data used in this study has a broader range of parameter uncertainty (GSD values); therefore, we cannot conclude that IO data is always more uncertain than process-based data.

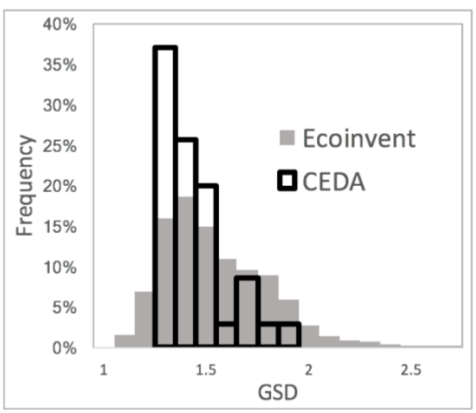

Figure 2. Geometric standard deviation (GSD) values for all process (ecoinvent) and input-output (CEDA) data used in the study (does not include the processes that had no quantified uncertainty or GSD = 1)

It is important to note that while the GSD values for each CEDA process used in our study were comparable to that of ecoinvent, there was additional uncertainty introduced through the use of IO data. As described in section (c) of the methodology, the contribution of each upstream process was based on an average of the total direct and indirect inputs of each commodity to the five jacket-related sectors in the CEDA 5 database. The standard deviation of these five contributions (relative standard deviation ranging from 0.03 – 1.11 for each commodity) was included in the MCSs by varying each of the CEDA-based technology (A) matrix parameters according to these corresponding standard deviations. Therefore, the overall uncertainty introduced through the use of CEDA data is higher than that of the ecoinvent inputs, but the broad range of GSD values in ecoinvent demonstrates that process-based LCA input data is not without uncertainty on its own.

Results

The total GWP of the process LCA for one jacket in step (a) was 15.9 kg CO_2eq. As previously mentioned, this is slightly (7%) lower than the reported results in the original Mistra study; the use of different versions of ecoinvent database and characterization factor data are likely to explain the difference. Using the hybrid LCA approach, input-output data was then used to fill in all the upstream data gaps during step (b). IO data was used for 36 additional processes (bringing the total to 229), a list of which is included in Table 3S in the supplemental information. The overall impacts increase significantly after hybridization (21.9kg CO2eq, or a 38% increase from step (a)), demonstrating a reduction in truncation error using the hybrid approach. Despite the large increase in the total GWP, the top five contributing processes do not change. This is expected, given that system boundaries and cut-offs in a process LCA should be defined to include the most significant unit processes in the life cycle.

Resulting probability distributions from the Monte Carlo simulations are portrayed in Figure 3 for each of the steps described in the study design: (a) process LCA approach using only the available process data, (b) hybrid LCA approach with all available process data and IO data to fill in the upstream data gaps, and (c) refined hybrid LCA approach by reducing uncertainty (individual GSD values) of the top-ten highest contributors to overall uncertainty. The standard deviation of the characterized results for climate change measured in GWP_{100} changed from 0.62 (a) to 0.75 (b) by the inclusion of IO data using the hybrid approach. After refining the top ten processes that contribute to uncertainty, the precision improves dramatically (standard deviation in (c) = 0.11) and the median remains closer to that of the unrefined hybrid LCA than of the baseline process LCA results (median of (a) = 15.9, (b) = 21.9, (c) = 21.7. Of the top-ten processes identified through a sensitivity analysis as the highest contributors to overall uncertainty, four were using process-based data and six were unit processes using input-output data, indicating that the higher expected uncertainty associated with the IO data used in the hybrid approach did not overpower the process LCA results.

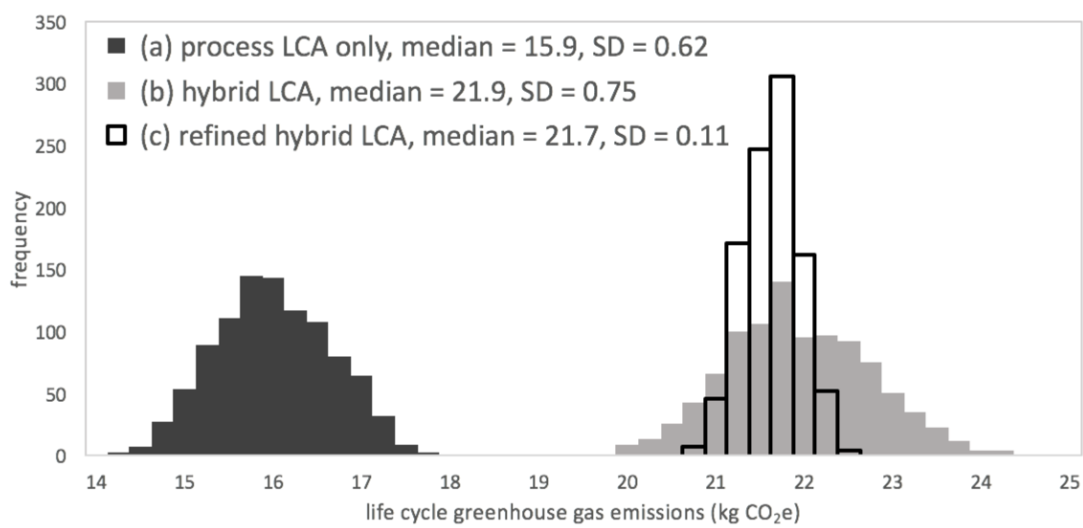

Figure 3. Monte Carlo simulation (MCS) distribution and median results at each study step: (a) process LCA only, (b) hybrid LCA with input-output (IO) data to fill in gaps, and (c) refined hybrid LCA with reduced geometric standard deviations (GSDs) for top ten processes contributing most to overall uncertainty

Step-wise analysis of hybridization and refinement of the jacket LCA case study shows the improvement of both accuracy and precision possible with the hybrid LCA approach. To elaborate on the hybridization process (step (b)) the hybridization was repeated with only one data gap filled in with IO data at a time, prioritizing the larger data gaps first. The point of this exercise was to demonstrate how the uncertainty changes, both in precision and accuracy, with the inclusion of each additional input-output process. Figure 4 displays the MCS results after each additional data gap is filled in with IO data using the hybrid method (left of the blue vertical line), as well as those results after each of the processes contributing most to overall uncertainty are refined (right of the blue vertical line). Precision improvements alone could be achieved without the use of the hybrid approach; however, accuracy would be difficult to address since truncation error is a prevalent outcome in the process-based approach to LCI data collection. Improving precision when using only the process LCA approach would therefore refine the results around a value that was knowingly inaccurate due to the underestimation caused by truncation error.

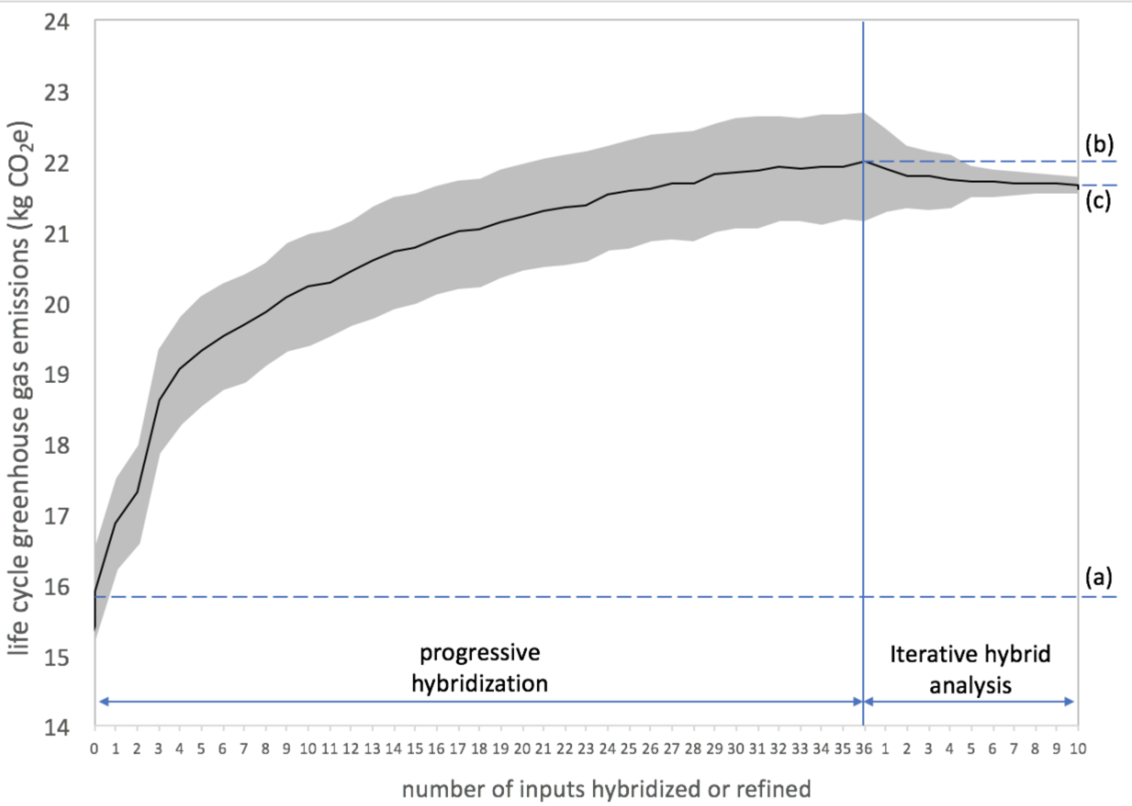

Figure 4. Progression of life cycle impact assessment (LCIA) results using the iterative hybrid LCA approach (grey represents the standard deviation of the Monte Carlo simulation (MCS) results at each step; white represents the median of the MCS results). Median values: (a) = 15.9, (b) = 21.9, (c) = 21.7.

Discussion

This study assessed the uncertainty implications of employing the hybrid LCA approach to address truncation error by considering both precision and accuracy. We selected an existing process LCA and used Monte Carlo simulation to analyze the shape and position of the distribution in the results after hybridizing one flow at a time. Accounting for known cut-offs due to process data gaps of an existing process LCA, we arrived at 5% higher mean and median life-cycle GHG emissions as a result of hybridization. The standard deviation remained consistently in the 0.62-0.78 range throughout the hybridization process. The magnitude of truncation error from undocumented cut-offs and system boundary decisions is unknown, but it is likely that what has been accounted for in our study is a subset of the total truncation.

It is notable that truncation error is unidirectional, meaning that it is always presented as an underestimation bias, while the errors in the input-output data, or other proxy data for cut-offs, are generally random.[4,49] When it comes to refinement of data to improve the quality of an LCA result, the distinction between IO or process cannot serve as the guide for choosing data; best quality data considering both precision and accuracy should be prioritized regardless of the distinction. In doing so, an LCA analyst should consider the trade-offs between precision and accuracy; i.e., inclusion of less precise data should be considered if its benefits for improving system completeness and accuracy outweigh the cost. For example, if one process contributes an overwhelming majority of the total impacts it may be unwise to use input-output data, since the introduction of less precise data for that process may spread the range of possible results too broad to be useful in decision making. The decisions associated with data selection are always based on the scope and objective of the LCA study, along with the subjective choices of the LCA practitioner. Furthermore, prioritizing the largest contributors to overall uncertainty can substantially reduce the time and resources needed for further improvement in the quality of LCA results. We therefore recommend the iterative procedure, starting from the rough but complete picture and progressively refining the key contributors to overall uncertainty.

Our study is limited by the existing uncertainty distribution data from both ecoinvent and CEDA. The subjectivity of the pedigree approach and reliance on expert judgement to estimate certain contributors to these uncertainties are also recognized as a limitation, and future research should focus on developing more objective and scientific alternatives to measure parameter uncertainty in both process-based and IO datasets.

While our work attempted to capture and assess uncertainty more holistically than in typical LCA studies, not all sources of uncertainty could be included in our assessment. Specifically, uncertainty associated with the technology matrix was not presented in the Mistra study and therefore not included in our analysis. Additionally, uncertainty of characterization factors in impact assessment was outside the scope of our study. Future work should address how to measure these sources of uncertainty as well.

Acknowledgements

We are thankful to Ms. Yuwei Qin, a PhD graduate student researcher at the Bren School of Environmental Science & Management, at the University of California, Santa Barbara (UCSB), for her comments on an earlier version of the manuscript. This publication was developed under Assistance Agreement No. 8355790 awarded by the U.S. Environmental Protection Agency to University of California Santa Barbara. It has not been formally reviewed by EPA. The views expressed in this document are solely those of the authors and do not necessarily reflect those of the Agency. EPA does not endorse any products or commercial services mentioned in this publication.

References

(1) Suh, S.; Huppes, G. Methods for Life Cycle Inventory of a product. *Journal of Cleaner Production*. 2015, 13, 687-697.

(2) Ward, H.; Wenz, L.; Steckel, J.C.; Minx, J.C. Truncation Error Estimates in Process Life Cycle Assessment Using Input-Output Analysis. *Journal of Industrial Ecology*. **2017**, online.

(3) Finnveden, G.; Hauschild, M. Z.; Ekvall, T.; Guinée, J. B.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in life cycle assessment. *Journal of Environmental Management*. **2009**, 91(1), 1-21.

(4) Suh, S.; Lenzen, M.; Treloar, G. J.; Hondo, H.; Horvath, A.; Huppes, G.; Jolliet, O.; Klann, U.; Krewitt, W.; Moriguchi, Y.; Munksgaard, J.; Norris, G. System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. *Environmental Science & Technology*. **2004**, 38(3), 657-664.

(5) Reap, J.; Roman, F.; Duncan, S.; Bras, B. A survey of unresolved problems in life cycle assessment. Part 1: goal and scope and inventory analysis. *International Journal of Life Cycle Assessment*. **2008**, 13, 290-300.

(6) Lave, L. B.; Cobas-Flores, E.; Hendrickson, C. T.; McMichael, F. C. Using Input-Output Analysis to Estimate Economy-wide Discharges. *Environmental Policy Analysis*. **1995**, 29(9) 420-426.

(7) Treloar, G. J. Extracting embodied energy paths from input-output tables. *Economic Systems Research*. **1997**, 9(4) 375-392.

(8) Lenzen, M. Errors in Conventional and Input-Output-based Life-Cycle Inventories. *Journal of Industrial Ecology*. **2001**, 4(4) 127-148.

(9) Williams, E. D.; Weber, C. L.; Hawkins, T. R. Hybrid Framework for Managing Uncertainty in Life Cycle Inventories. *Journal of Industrial Ecology*. **2009**, 13(6), 928-944.

(10) Reich-Weiser, C. Ace, J., Brooks, C., Suh, S., **2010**: An Iterative Hybrid Carbon Footprint, In: Murray J. and Wood, R. (Eds.), The Sustainability Practitioner's Guide to Input-Output Analysis, Common Ground Publishing, Urbana-Champaign, Il, USA.

(11) Huang, Y.; Lenzen, M.; Weber, C. L.; Murray, J.; Matthews, H. S. The role of input-output analysis for the screening of corporate carbon footprints. *Economic Systems Research*. **2009**, 21(3), 217-242.

(12) Lenzen, M.; Treloar, G. Differential Convergence of Life-Cycle Inventories toward Upstream Production Layers: Implications for Life-Cycle Assessment. *Journal of Industrial Ecology*. **2003**, 6(3-4), 137-160.

(13) Suh, S. Functions, commodities and environmental impacts in an ecological-economic model. *Ecological Economics*. **2004**, 48(4), 451-467.

(14) Rowley, H. V.; Lundie, S.; Peters, G. M. A hybrid life cycle assessment model for comparison with conventional methodologies in Australia. *The International Journal of Life Cycle Assessment*. **2009**, 14(6), 508-516.

(15) Crawford, R. H.; Stephan, A. The significance of embodied energy in certified passive houses. *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*. **2013**, 7(6), 427-433.

(16) Majeau-Bettez, G.; Hawkins, T. R.; Stromman, A. H. Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues. *Environmental Science & Technology*. **2011**, 45(23), 10170-10777.

(17) Beltran, A. M.; Prado, V.; Vivanco, D. F.; Hendriksson, P. J. G.; Guinée, J. B.; Heijungs, R. Quantified Uncertainties in Comparative Life Cycle Assessment: What Can Be Concluded? *Environmental Science & Technology*. **2018**, online.

(18) Guo, M.; Murphy, R. J. LCA data quality: Sensitivity and uncertainty analysis. *Science of the Total Environment*. **2012**, (435-436), 230-243.

(19) Heijungs, R.; Huijbregts, M. A. J. A Review of Approaches to Treat Uncertainty in LCA. *9th International Congress on Environmental Modelling and Software*. **2004**, 197.

(20) Bevington, P. R.; Robinson, D. K. *Data reduction and error analysis for the physical sciences. Second edition*. McGraw-Hill, Inc., New York, 1992.

(21) Funtowicz, S. O.; Ravetz, J. R. *Uncertainty and quality in science for policy*. Kluwer Academic Publishers, Dordrecht, 1990.

(22) Morgan, M. G.; Henrion, M. *Uncertainty. A guide to dealing with uncertainty in quantitative risk and policy analysis*. Cambridge University Press, Cambridge, 1990.

(23) Hofstetter, P. *Perspectives in life cycle impact assessment: A structured approach to combine models of the technosphere, ecosphere, and valuesphere.* Boston: Kluwer Academic, 1998.

(24) Bedford, T.; Cooke, R. *Probabilistic risk analysis. Foundations and methods.* Cambridge University Press, Cambridge, 2001.

(25) Huijbregts, M. A. J. *Uncertainty and variability in environmental life-cycle assessment*. PhD thesis, Universiteit van Amsterdam, Amsterdam, 2001.

(26) US-EPA. *Exposure factors handbook.* EPA, Washington, 1989.

(27) Lloyd, S. M.; Ries, R. Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches. *Journal of Industrial Ecology*. **2007**, 11(1), 161-179.

(28) Hellweg, S.; Milà I Canals, L. Emerging approaches, challenges and opportunities in life cycle assessment. *Science (Washington, DC, U.S.)* **2014**, 344(6188), 1109-1113.

(29) Ross, S.; Evans, D.; Webber, M. How LCA Studies Deal with Uncertainty. *International Journal of Life Cycle Assessment*. **2002**, 7(1), 47-52.

(30) Clavreul, J.; Guyonnet, D.; Tonini, D.; Christensen, T. H. Stochastic and epistemic uncertainty propogration in LCA. *International Journal of Life Cycle Assessment*. **2013**, 18, 1392-1403.

(31) Mattila, T. J.; Pakarinen, S.; Sokka, L. Quantifying the Total Environmental Impacts of an Industrial Symbiosis – a Comparison of Process-, Hybrid and Input-Output Life Cycle Assessment. *Environmental Science & Technology*. **2010**, 44(11), 4309-4314.

(32) BS ISO 5725-1: "Accuracy (trueness and precision) of measurement methods and results - Part 1: General principles and definitions.", p.1 (1994)

(33) North Atlantic Treaty Organization, NATO Standardization Agency AAP-6 – Glossary of terms and definitions, p 43.

(34) Hellmann, J. J.; Fowler, G. W. Bias, Precision, and Accuracy of Four Measures of Species Richness. *Ecological Applications*. **1999**, 9(3), 824-834.

(35) Walther, B. A.; Moore, J. L. The concepts of bias, precision and accuracy, and their use in testing the performance of species richness estimators, with a literature review of estimator performance. *Ecography*. **2005**, 28(6), 815-829.

(36) Selvik, J. T.; Abrahamsen, E. B. On the meaning of accuracy and precision in a risk analysis context. *Journal of Risk and Reliability*. **2017**, 23(2), 91-100.

(37) Brandão, M.; Clift, R.; Cowie, A.; Greenhalgh, S. Letter to the Editor: The Use of Life Cycle Assessment in the Support of Robust (Climate) Policy Making: Comment on "Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation…" *Journal of Industrial Ecology*. **2014**, 18(3), 461-463.

(38) Björklund, A. E. Survey of Approaches to Improve Reliability in LCA. *International Journal of Life Cycle Assessment*. **2002**, 7(2), 64-72.

(39) Roos, S.; Sandin, G.; Zamani, B.; Peters, G. Environmental assessment of Swedish fashion consumption. *Mistra Future Fashion Consortium*. **2015**.

(40) Suh, S.; Huppes, G. Methods for Life Cycle Inventory of a product. *Journal of Cleaner Production*. **2005**, 13, 687-697.

(41) Suh, S. Functions, commodities and environmental impacts in an ecological – economic model. *Ecological Economics*. **2004**, 48, 451-467.

(42) Heijungs, R.; Suh, S. *The computational structure of life cycle assessment.* Springer Science & Business Media, **2002**.

(43) Ecoinvent Centre. Ecoinvent data v3.1. Available at: http://www.ecoinvent.org.

(44) http://www.ecoinvent.org/support/faqs/methodology-of-ecoinvent-3/how-to-interpret-the-uncertainty-fields-in-ecoinvent.html

(45) Qin, Y., Suh, S. What distribution function do life cycle inventories follow? *International Journal of Life Cycle Assessment.* **2017**, 22(7), 1138-1145.

(46) Weidema, B. P.; Wesnaes, M. S. Data quality management for life cycle inventories – an example of using data quality indicators. *Journal of Cleaner Production*. **1996**, 4(3-4), 167-174.

(47) Reap, J.; Roman, F.; Duncan, S.; Bras, B. A survey of unresolved problems in life cycle assessment. Part 2: impact assessment and interpretation. *International Journal of Life Cycle Assessment*. **2008**, 13, 374-388.

(48) Comprehensive Environmental Data Archive (CEDA) version 5: 2016. Industrial Ecology Research Service (IERS), Goleta, CA, USA.

(49) Suh, S. and Huppes, G. Missing inventory estimation tool using extended input-output analysis. *The International Journal of Life Cycle Assessment*. **2002**, *7*(3), 134-140.

(50) Yang, Y., Heijungs, R. & Brandão, M. Hybrid life cycle assessment (LCA) does not necessarily yield more accurate results than process-based LCA. *Journal of Cleaner Production*. **2017**, 150, 237-242.

(51) Pomponi, F. & Lenzen, M. Hybrid life cycle assessment (LCA) will likely yield more accurate results than process-based LCA. *Journal of Cleaner Production.* **2018**, 176, 210-215.

(52) Peters, G.P. & Hertwich, E.G. A comment on “Functions, commodities and environmental impacts in an ecological-economic model”. *Ecological Economics*. **2006**, 59(1), 1-6.

(53) Olivetti, E., Patanavanich, S. & Kirchain, R. Exploring the Viability of Probabilistic Under-Specification To Streamline Life Cycle Assessment. *Environmental Science & Technology*. **2013**, 47, 5208-5216.

Appendices

Uncertainty: classifications and definitions

Information without the understanding of its uncertainty has very little meaning. [18] Beltran and her colleagues,[17] for example, compared results from five different uncertainty-statistic methods (USMs) with deterministic results in a case study. Their work and others have demonstrated that without any characterization of significance or likelihood, deterministic comparative LCA results are often oversimplified to be appropriate for decision making and outcomes could potentially be reversed when uncertainty calculations are considered.[18]

Uncertainty in LCA has been defined, categorized, and characterized in many different ways over the last few decades. Heijungs and Huijbregts summarized several different studies that classified uncertainties into categories (outlined in this section) and suggested a division into three types: (1) data for which no value is available, (2) data for which an inappropriate value is available, and (3) data for which more than one value is available.[19] They applied this same three-type categorization to relationships and choices. Bevington and Robinson[20] described uncertainty in physical sciences research as falling into two categories: systematic errors and random errors. Funtowicz and Ravetz recommended that data uncertainty, model uncertainty and completeness uncertainty be addressed in scientific results intended for use in policy.[21] Morgan and Henrion suggested statistical variation, subjective judgement, linguistic imprecision, variability, inherent randomness, disagreement and approximation as the different types of uncertainty that should be addressed in a similar context as described by Funtowicz and Ravetz.[22] Their categorization has been referenced in subsequent publications from Hofstetter (1998) and Lloyd and colleagues (2007) specifically addressing uncertainty in the context of LCA.[23,27] Uncertainty categorization has been explored in the risk assessment field, as the US EPA defines uncertainty in the *Exposure Factors Handbook* (1998) as either scenario uncertainty, parameter uncertainty or model uncertainty,[26] and Bedford and Cooke discuss the following longer list of categories as being relevant to probabilistic risk assessment: aleatory uncertainty, epistemic uncertainty, parameter uncertainty, data uncertainty, model uncertainty, ambiguity and volitional uncertainty.[24]

Similar to in other disciplines, there is still no consensus on categorization of uncertainty in LCA. Huijbregts published one of the first (2001) comprehensive classifications specifically in the context of LCA: parameter uncertainty, model uncertainty, uncertainty due to choices, spatial variability, temporal variability, variability between sources and objects.[25] Later, Lloyd and her colleagues identified seven sources of uncertainty and variability – random error and statistical variation, systematic error and subjective judgement, linguistic imprecision, variability, inherent randomness and unpredictability, expert uncertainty and disagreement, approximation – and categorize them within one of three groups based on LCA modeling component: parameter (input data), scenario (normative choices), and model (mathematical relationships).[27] Williams and his colleagues considered uncertainty in the context of different LCA approaches (process, IO, hybrid) and classified the different sources of uncertainty: data, cut off, aggregation, geographic and temporal.[9]

Uncertainty analyses in LCA practice

Though many dimensions of uncertainty are discussed in the LCA literature, few are implemented in LCA studies. Lloyd and her colleagues conducted a literature review of LCA case studies published in journal or conference proceedings that quantified uncertainty and that were freely available. Of the identified 24 studies 100% addressed parameter uncertainty, 38% addressed scenario uncertainty and 33% addressed model uncertainty (only 7% considered both scenario and model uncertainty).[27] There are many methods available for uncertainty assessment, but several authors have found that the application of these methods is sparse.[17,28] In 2002, Ross and colleagues surveyed 30 LCA studies to evaluate the extent to which uncertainty is dealt with in practice. Of these, 14 (47%) mentioned uncertainty, 2 (7%) performed qualitative uncertainty analysis, and 1 (3%) performed quantitative uncertainty analysis.[29]

These observations, which were made more than a decade ago, are still applicable today. We conducted a brief literature review in February 2018 to evaluate whether the findings in previous literature are consistent with the current use and types of uncertainty assessment in LCA case studies. A search was performed in Web of Science under the following constraints: TITLE: "Life Cycle Assessment" OR "Life Cycle Analysis" OR LCA, TIME: 2010-2018. We collected the top thirty most-cited LCA case studies from this search (excluding methodological and review papers). Table 1S shows an analysis of the top 36 most cited LCA case studies published since 2010. It shows similar findings to previous reviews: a large number of papers (one-third) do not measure uncertainty at all, and a majority of those that do primarily focus on parameter uncertainty.

Table 1s. Uncertainty assessment in the most cited recent LCA case studies (2010-2018)

Case Study Sector	*Types of Uncertainty Quantified*

(total papers reviewed)	*Parameter*	*Model*	*Truncation Error*	*Aggregation*	*None*
biofuel (14)	11	1			4
food and ag (4)	3		1		1
building materials (3)					3
solar (3)	1				2
electric vehicles (2)	2				
consumer goods (2)	1	1			
pulp and paper (1)			1	1	
TOTAL	18	2	2	1	10

Non-parametric, epistemological uncertainty is discussed sparsely in the literature and truncation error is rarely included in uncertainty assessment for LCA case studies. The sole paper in the list of papers that we reviewed that did a full assessment of truncation error was a study comparing the process, IO and hybrid LCA approaches by Mattila and colleagues.[31] Table 2S lists all of the papers included in the review.

Clavreul and her colleagues (2013) proposed a method to addressed epistemic uncertainty by combining probability theory for stochastic uncertainty with possibility theory for epistemic uncertainty, generating results that include both probability distributions and fuzzy intervals to account for all possible values.[30] Though epistemic uncertainty is addressed in this work, the focus is on parameter uncertainty and uncertainty associated with expert judgement, not on epistemic uncertainty associated with unknowns related to the system boundary or truncation error. More recently Ward and colleagues demonstrated a viable methodology to measure truncation error in process LCA studies through a combination of IO and hybrid LCA approaches.[2] Ward's work offers a viable solution to begin quantifying truncation error in applications of LCA, but currently estimation of truncation error in process LCA is not a common practice.

Table 2S. Publications included in recent literature review

Author(s)	Title	Source Publication	Year Published
Yang, J; Xu, M; Zhang, XZ; Hu, QA; Sommerfeld, M; Chen, YS	Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance	BIORESOURCE TECHNOLOGY	2011
Stephenson, AL; Kazamia, E; Dennis, JS; Howe, CJ; Scott, SA; Smith, AG	Life-Cycle Assessment of Potential Algal Biodiesel Production in the United Kingdom: A Comparison of Raceways and Air-Lift Tubular Bioreactors	ENERGY & FUELS	2010
You, FQ; Tao, L; Graziano, DJ; Snyder, SW	Optimal design of sustainable cellulosic biofuel supply chains: Multiobjective optimization coupled with life cycle assessment and input-output analysis	AICHE JOURNAL	2012
Roberts, KG; Gloy, BA; Joseph, S; Scott, NR; Lehmann, J	Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential	ENVIRONMENTAL SCIENCE & TECHNOLOGY	2010
Sander, K; Murthy, GS	Life cycle analysis of algae biodiesel	INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT	2010
Campbell, PK; Beer, T; Batten, D	Life cycle assessment of biodiesel production from microalgae in ponds	BIORESOURCE TECHNOLOGY	2011
Cherubini, F; Ulgiati, S	Crop residues as raw materials for biorefinery systems - A LCA case study	APPLIED ENERGY	2010
Hawkins, TR; Singh, B; Majeau-Bettez, G; Stromman, AH	Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles	JOURNAL OF INDUSTRIAL ECOLOGY	2013
Bribian, IZ; Capilla, AV; Uson, AA	Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential	BUILDING AND ENVIRONMENT	2011
Collet, P; Helias, A; Lardon, L; Ras, M; Goy, RA; Steyer, JP	Life-cycle assessment of microalgae culture coupled to biogas production	BIORESOURCE TECHNOLOGY	2011
Espinosa, N; Garcia-Valverde, R; Urbina, A; Krebs, FC	A life cycle analysis of polymer solar cell modules prepared using roll-to-roll methods under ambient conditions	SOLAR ENERGY MATERIALS AND SOLAR CELLS	2011
Zackrisson, M; Avellan, L; Orlenius, J	Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles - Critical issues	JOURNAL OF CLEANER PRODUCTION	2010
Brentner, LB; Eckelman, MJ; Zimmerman, JB	Combinatorial Life Cycle Assessment to Inform Process Design of Industrial Production of Algal Biodiesel	ENVIRONMENTAL SCIENCE & TECHNOLOGY	2011
Beauchemin, KA; Janzen, HH; Little, SM; McAllister, TA; McGinn, SM	Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study	AGRICULTURAL SYSTEMS	2010
Van den Heede, P; De Belie, N	Environmental impact and life cycle assessment (LCA) of traditional and 'green'	CEMENT & CONCRETE COMPOSITES	2012

	concretes: Literature review and theoretical calculations		
Gong, J; Darling, SB; You, FQ	Perovskite photovoltaics: life-cycle assessment of energy and environmental impacts	ENERGY & ENVIRONMENTAL SCIENCE	2015
Cherubini, F; Jungmeier, G	LCA of a biorefinery concept producing bioethanol, bioenergy, and chemicals from switchgrass	INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT	2010
Nemecek, T; Dubois, D; Huguenin-Elie, O; Gaillard, G	Life cycle assessment of Swiss farming systems: I. Integrated and organic farming	AGRICULTURAL SYSTEMS	2011
Peters, GM; Rowley, HV; Wiedemann, S; Tucker, R; Short, MD; Schulz, M	Red Meat Production in Australia: Life Cycle Assessment and Comparison with Overseas Studies	ENVIRONMENTAL SCIENCE & TECHNOLOGY	2010
Foley, JM; Rozendal, RA; Hertle, CK; Lant, PA; Rabaey, K	Life Cycle Assessment of High-Rate Anaerobic Treatment, Microbial Fuel Cells, and Microbial Electrolysis Cells	ENVIRONMENTAL SCIENCE & TECHNOLOGY	2010
Rehl, T; Muller, J	Life cycle assessment of biogas digestate processing technologies	RESOURCES CONSERVATION AND RECYCLING	2011
Wang, B; Gebreslassie, BH; You, FQ	Sustainable design and synthesis of hydrocarbon biorefinery via gasification pathway: Integrated life cycle assessment and technoeconomic analysis with multiobjective superstructure optimization	COMPUTERS & CHEMICAL ENGINEERING	2013
Espinosa, N; Garcia-Valverde, R; Urbina, A; Lenzmann, F; Manceau, M; Angmo, D; Krebs, FC	Life cycle assessment of ITO-free flexible polymer solar cells prepared by roll-to-roll coating and printing	SOLAR ENERGY MATERIALS AND SOLAR CELLS	2012
Hossain, AK; Davies, PA	Plant oils as fuels for compression ignition engines: A technical review and life-cycle analysis	RENEWABLE ENERGY	2010
Jury, C; Benetto, E; Koster, D; Schmitt, B; Welfring, J	Life Cycle Assessment of biogas production by monofermentation of energy crops and injection into the natural gas grid	BIOMASS & BIOENERGY	2010
Chang, YA; Ries, RJ; Wang, YW	The embodied energy and environmental emissions of construction projects in China: An economic input-output LCA model	ENERGY POLICY	2010
Mattila, TJ; Pakarinen, S; Sokka, L	Quantifying the Total Environmental Impacts of an Industrial Symbiosis - a Comparison of Process-, Hybrid and Input-Output Life Cycle Assessment	ENVIRONMENTAL SCIENCE & TECHNOLOGY	2010
Seabra, JEA; Macedo, IC; Chum, HL; Faroni, CE; Sarto, CA	Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use	BIOFUELS BIOPRODUCTS & BIOREFINING-BIOFPR	2011
Walser, T; Demou, E; Lang, DJ; Hellweg, S	Prospective Environmental Life Cycle Assessment of Nanosilver T-Shirts	ENVIRONMENTAL SCIENCE & TECHNOLOGY	2011

Shen, L; Worrell, E; Patel, MK	Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling	RESOURCES CONSERVATION AND RECYCLING	2010
Sills, DL; Paramita, V; Franke, MJ; Johnson, MC; Akabas, TM; Greene, CH; Testert, JW	Quantitative Uncertainty Analysis of Life Cycle Assessment for Algal Biofuel Production	ENVIRONMENTAL SCIENCE & TECHNOLOGY	2013
Hertwich, EG; Gibon, T; Bouman, EA; Arvesen, A; Suh, S; Heath, GA; Bergesen, JD; Ramirez, A; Vega, MI; Shi, L	Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies	PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	2015
Cuellar-Franca, RM; Azapagic, A	Environmental impacts of the UK residential sector: Life cycle assessment of houses	BUILDING AND ENVIRONMENT	2012
Bigum, M; Brogaard, L; Christensen, TH	Metal recovery from high-grade WEEE: A life cycle assessment	JOURNAL OF HAZARDOUS MATERIALS	2012
Poeschl, M; Ward, S; Owende, P	Environmental impacts of biogas deployment - Part II: life cycle assessment of multiple production and utilization pathways	JOURNAL OF CLEANER PRODUCTION	2012
Nemecek, T; Huguenin-Elie, O; Dubois, D; Gaillard, G; Schaller, B; Chervet, A	Life cycle assessment of Swiss farming systems: II. Extensive and intensive production	AGRICULTURAL SYSTEMS	2011

Table 3s. Ranked average contribution and uncertainty of commodity contributions to the five jacket-production-related CEDA sectors and identification of those used in the hybridization.

CEDA Code	Commodity Description	Average of direct flows (from CEDA Aa matrix) to the five jacket-production-related sectors (USD / USD production)*	Standard deviation of direct flows (from CEDA Aa matrix) to the five jacket-production-related sectors (USD / USD production)*	Included (IN) or Excluded (EX) in Hybridization?
3252A0	Synthetic rubber and artificial and synthetic fibers and filaments manufacturing	0.138	0.152	EX
313200	Fabric mills	0.059	0.050	EX
313300	Textile and fabric finishing and fabric coating mills	0.053	0.044	EX
420000	Wholesale trade	0.049	0.009	EX
111900	Other crop farming	0.045	0.083	EX
550000	Management of companies and enterprises	0.037	0.014	IN
313100	Fiber, yarn, and thread mills	0.036	0.015	EX
33329A	Other industrial machinery manufacturing	0.032	0.016	IN

325211	Plastics material and resin manufacturing	0.022	0.023	EX
315000	Apparel manufacturing	0.020	0.036	EX
484000	Truck transportation	0.016	0.005	EX
221100	Electric power generation, transmission, and distribution	0.011	0.006	EX
112A00	Animal production, except cattle and poultry and eggs	0.009	0.007	EX
221200	Natural gas distribution	0.008	0.006	EX
541300	Architectural, engineering, and related services	0.008	0.003	IN
541800	Advertising, public relations, and related services	0.007	0.004	IN
325130	Synthetic dye and pigment manufacturing	0.007	0.009	EX
233230	Manufacturing structures	0.006	0.002	IN
524100	Insurance carriers	0.005	0.005	IN
322210	Paperboard container manufacturing	0.005	0.003	EX
316000	Leather and allied product manufacturing	0.005	0.009	EX
314900	Other textile product mills	0.005	0.006	EX
52A000	Monetary authorities and depository credit intermediation	0.005	0.001	IN
326110	Plastics packaging materials and unlaminated film and sheet manufacturing	0.005	0.006	EX
325520	Adhesive manufacturing	0.004	0.004	EX
5419A0	Marketing research and all other miscellaneous professional, scientific, and technical services	0.004	0.001	IN
324110	Petroleum refineries	0.004	0.002	EX
332800	Coating, engraving, heat treating and allied activities	0.004	0.002	EX
533000	Lessors of nonfinancial intangible assets	0.004	0.003	IN

561900	Other support services	0.004	0.006	IN
331200	Steel product manufacturing from purchased steel	0.003	0.007	EX
522A00	Nondepository credit intermediation and related activities	0.003	0.001	IN
325190	Other basic organic chemical manufacturing	0.003	0.003	EX
541100	Legal services	0.003	0.001	IN
332710	Machine shops	0.003	0.002	IN
325610	Soap and cleaning compound manufacturing	0.003	0.005	EX
541511	Custom computer programming services	0.003	0.000	IN
2332A0	Commercial structures, including farm structures	0.003	0.001	IN
561700	Services to buildings and dwellings	0.003	0.001	IN
561400	Business support services	0.003	0.002	IN
322120	Paper mills	0.002	0.003	EX
562000	Waste management and remediation services	0.002	0.001	EX
327200	Glass and glass product manufacturing	0.002	0.004	IN
531ORE	Other real estate	0.002	0.002	IN
493000	Warehousing and storage	0.002	0.001	IN
481000	Air transportation	0.002	0.000	EX
517110	Wired telecommunications carriers	0.002	0.001	IN
518200	Data processing, hosting, and related services	0.002	0.001	IN
541200	Accounting, tax preparation, bookkeeping, and payroll services	0.002	0.001	IN
339990	All other miscellaneous manufacturing	0.002	0.004	IN
230301	Nonresidential maintenance and repair	0.002	0.001	IN

334413	Semiconductor and related device manufacturing	0.002	0.001	IN
212100	Coal mining	0.002	0.002	EX
33299B	Other fabricated metal manufacturing	0.002	0.001	IN
561300	Employment services	0.002	0.001	IN
325180	Other basic inorganic chemical manufacturing	0.002	0.002	EX
722211	Limited-service restaurants	0.002	0.000	EX
482000	Rail transportation	0.002	0.001	EX
S00300	Noncomparable imports	0.002	0.001	IN
331110	Iron and steel mills and ferroalloy manufacturing	0.001	0.003	EX
811300	Commercial and industrial machinery and equipment repair and maintenance	0.001	0.001	IN
541400	Specialized design services	0.001	0.001	IN
561600	Investigation and security services	0.001	0.001	IN
333993	Packaging machinery manufacturing	0.001	0.001	IN
336112	Light truck and utility vehicle manufacturing	0.001	0.000	IN
333920	Material handling equipment manufacturing	0.001	0.000	IN
334418	Printed circuit assembly (electronic assembly) manufacturing	0.001	0.001	IN
221300	Water, sewage and other systems	0.001	0.001	EX
322130	Paperboard mills	0.001	0.001	EX

*Five sectors were considered in the analysis to be directly relevant to the jacket's upstream production: (1) fiber, yarn, and thread mills, (2) fabric mills, (3) textile and fabric finishing and fabric coating mills, (4) other textile product mills, and (5) apparel manufacturing

Table 4S Sensitivity Analysis Results

Sensitivity Ranking	Standard Deviation of Monte Carlo Simulation	Process for which uncertainty was included	Data Source
1	0.4351	Tetrafluoroethylene, at plant/RER S	Ecoinvent
2	0.4157	Electricity, medium voltage, at grid/CN S	Ecoinvent
3	0.3317	Other real estate	CEDA
4	0.1655	Transport, passenger car, medium size, petrol, EURO 5 {RoW}| transport, passenger car, medium size, petrol, EURO 5 | APOS, S	Ecoinvent
5	0.1642	Management of companies and enterprises	CEDA
6	0.1094	Other industrial machinery manufacturing	CEDA
7	0.0801	Electricity, natural gas, at power plant/UCTE S	Ecoinvent
8	0.0751	Glass and glass product manufacturing	CEDA
9	0.0418	Advertising, public relations, and related services	CEDA
10	0.0408	Architectural, engineering, and related services	CEDA
11	0.0317	Waste incineration of fossil based textile fraction in municipal solid waste (MSW), SE	Ecoinvent
12	0.0271	Insurance carriers	CEDA
13	0.0271	Polyethylene terephthalate, granulate, amorphous, at plant/RER S	Ecoinvent
14	0.0249	Manufacturing structures	CEDA
15	0.0247	Nonresidential maintenance and repair	CEDA
16	0.0232	Light truck and utility vehicle manufacturing	CEDA
17	0.0230	Warehousing and storage	CEDA
18	0.0208	Machine shops	CEDA
19	0.0197	All other miscellaneous manufacturing	CEDA
20	0.0192	Disposal, sludge from pulp and paper production, 25% water, to sanitary landfill/CH EcoInvent System	Ecoinvent
21	0.0191	Disposal, sludge from pulp and paper production, 25% water, to sanitary landfill/CH S	Ecoinvent
22	0.0189	Transport, regular bus/CH S	Ecoinvent
23	0.0186	Legal services	CEDA

24	0.0181	Other fabricated metal manufacturing	CEDA
25	0.0171	Nondepository credit intermediation and related activities	CEDA
26	0.0169	Semiconductor and related device manufacturing	CEDA
27	0.0156	Monetary authorities and depository credit intermediation	CEDA
28	0.0155	Commercial structures, including farm structures	CEDA
29	0.0153	Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH S	Ecoinvent
30	0.0136	Services to buildings and dwellings	CEDA
31	0.0131	Lessors of nonfinancial intangible assets	CEDA
32	0.0127	Custom computer programming services	CEDA
33	0.0121	Marketing research and all other miscellaneous professional, scientific, and technical services	CEDA
34	0.0117	Accounting, tax preparation, bookkeeping, and payroll services	CEDA
35	0.0113	Other support services	CEDA
36	0.0111	Heat, light fuel oil, at boiler 10kW, non-modulating/CH S	Ecoinvent
37	0.0105	Wired telecommunications carriers	CEDA
38	0.0104	Compressed air, average generation, >30kW, 6 bar gauge, at compressor/RER S	Ecoinvent
39	0.0099	Transport, lorry 16-32t, EURO5/RER S	Ecoinvent
40	0.0095	Printed circuit assembly (electronic assembly) manufacturing	CEDA
41	0.0094	Steel, low-alloyed, at plant/RER S	Ecoinvent
42	0.0093	Aniline, at plant/RER S	Ecoinvent
43	0.0089	Data processing, hosting, and related services	CEDA
44	0.0087	Business support services	CEDA
45	0.0081	Transport, transoceanic freight ship/OCE S	Ecoinvent
46	0.0071	Employment services	CEDA
47	0.0071	Waste incineration of textile fraction of industrial waste - no credits	Ecoinvent

48	0.0069	Material handling equipment manufacturing	CEDA
49	0.0068	Steel product manufacturing, average metal working/RER S	Ecoinvent
50	0.0064	Specialized design services	CEDA
51	0.0057	Commercial and industrial machinery and equipment repair and maintenance	CEDA
52	0.0050	Ethoxylated alcohols (AE3), petrochemical, at plant/RER S	Ecoinvet
53	0.0047	Packaging film, low density polyethylene {GLO}| market for | APOS, S	Ecoinvent
54	0.0046	Investigation and security services	CEDA
55	0.0044	Electricity, oil, at power plant/UCTE S	Ecoinvent
56	0.0042	Hard coal, burned in industrial furnace 1-10MW/RER S	Ecoinvent
57	0.0038	Electricity, hard coal, at power plant/CN S	Ecoinvent
58	0.0038	Electricity, high voltage, at grid/SE S	Ecoinvent
59	0.0035	Transport, passenger car, medium size, petrol, EURO 5 {RER}| transport, passenger car, medium size, petrol, EURO 5 | APOS, S	Ecoinvent
60	0.0033	Brass, at plant/CH S	Ecoinvent
61	0.0032	Packaging machinery manufacturing	CEDA
62	0.0029	Formic acid, at plant/RER S	Ecoinvent
63	0.0026	Packaging film, LDPE, at plant/RER S	Ecoinvent
64	0.0026	Polyurethane, flexible foam, at plant/RER S	Ecoinvent
65	0.0024	Heat, natural gas, at industrial furnace >100kW/RER S	Ecoinvent
66	0.0024	Electricity, low voltage, at grid/SE S	Ecoinvent
67	0.0024	Heat, light fuel oil, at boiler 100kW condensing, non-modulating/CH EcoInvent System	Ecoinvent
68	0.0022	Modified starch, at plant/RER S	Ecoinvent
69	0.0021	Nylon 6, at plant/RER S	Ecoinvent
70	0.0020	Ethoxylated alcohols (AE7), petrochemical, at plant/RER S	Ecoinvent
71	0.0019	Paper, recycling, with deinking, at plant/RER S	Ecoinvent

72	0.0018	Acrylic acid, at plant/RER S	Ecoinvent
73	0.0014	Solid unbleached board {GLO}| market for | APOS, S	Ecoinvent
74	0.0012	Lubricating oil, at plant/RER S	Ecoinvent
75	0.0012	Heat, softwood chips from forest, at furnace 1000kW/CH S	Ecoinvent
76	0.0011	Transport, lorry 7.5-16t, EURO5/RER S	Ecoinvent
77	0.0010	Esterquat {RER}| treatment of tallow to | APOS, S	Ecoinvent
78	0.0010	Water, ultrapure, at plant/GLO S	Ecoinvent
79	0.0009	Metal product manufacturing, average metal working/RER S	Ecoinvent
80	0.0007	Lubricating oil, at plant/RER EcoInvent System	Ecoinvent
81	0.0007	Cotton fibre {CN}| cotton production | APOS, S	Ecoinvent
82	0.0007	Electricity, high voltage, at grid/CN S	Ecoinvent
83	0.0006	Transport, lorry 16-32t, EURO3/RER S	Ecoinvent
84	0.0005	Phosphoric acid, industrial grade, 85% in H2O, at plant/RER S	Ecoinvent
85	0.0004	Heat, natural gas, at boiler modulating <100kW/RER S	Ecoinvent
86	0.0003	Acetic acid, without water, in 98% solution state {RER}| acetic acid production, product in 98% solution state | APOS, S	Ecoinvent
87	0.0003	Calcium chloride, CaCl2, at plant/RER S	Ecoinvent
88	0.0003	Ethylene glycol monoethyl ether, at plant/RER S	Ecoinvent
89	0.0002	Transport, lorry 3.5-7.5t, EURO5/RER S	Ecoinvent
90	0.0002	Peat, burned in power plant/NORDEL S	Ecoinvent
91	0.0001	Chemical, organic {GLO}| production | APOS, S	Ecoinvent
92	0.0001	Transport, regular bus {CH}| processing | APOS, S	Ecoinvent
93	0.0001	Hydrogen peroxide, 50% in H2O, at plant/RER S	Ecoinvent
94	<0.0001	Noncomparable imports	CEDA
95	<0.0001	Cotton, based on Cotton Inc. data in GaBi	Cotton Inc.
96	<0.0001	Benzo[thia]diazole-compounds, at regional storehouse/RER S	Ecoinvent

97	<0.0001	Acrylic acid {RER}| production | APOS, S	Ecoinvent
98	<0.0001	Acrylic dispersion, without water, in 65% solution state {RER}| acrylic dispersion production, product in 65% solution state | APOS, S	Ecoinvent
99	<0.0001	Activated silica {GLO}| market for | APOS, S	Ecoinvent
100	<0.0001	Ethoxylated alcohol (AE7) {RER}| ethoxylated alcohol (AE7) production, petrochemical | APOS, S	Ecoinvent
101	<0.0001	Alkylbenzene sulfonate, linear, petrochemical {RER}| production | APOS, S	Ecoinvent
102	<0.0001	Ammonium sulphate, as N, at regional storehouse/RER S	Ecoinvent
103	<0.0001	Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	Ecoinvent
104	<0.0001	Antimony, at refinery/CN S	Ecoinvent
105	<0.0001	Sodium carbonate from ammonium chloride production, at plant/GLO S	Ecoinvent
106	<0.0001	Transport, passenger, aircraft {RER}| intercontinental | APOS, S	Ecoinvent
107	<0.0001	Cobalt, at plant/GLO S	Ecoinvent
108	<0.0001	Tap water {RoW}| market for | APOS, S	Ecoinvent
109	<0.0001	Corrugated board base paper, kraftliner, at plant/RER S	Ecoinvent
110	<0.0001	Maleic anhydride, at plant/RER S	Ecoinvent
111	<0.0001	Diethanolamine, at plant/RER S	Ecoinvent
112	<0.0001	Dimethylacetamide, at plant/GLO S	Ecoinvent
113	<0.0001	Dimethyl sulphate, at plant/RER S	Ecoinvent
114	<0.0001	Disposal, packaging cardboard, 19.6% water, to municipal incineration/CH S	Ecoinvent
115	<0.0001	Disposal, packaging paper, 13.7% water, to municipal incineration/CH S	Ecoinvent
116	<0.0001	Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH S	Ecoinvent
117	<0.0001	Disposal, textiles, soiled, 25% water, to municipal incineration/CH S	Ecoinvent

118	<0.0001	Organophosphorus-compound, unspecified {RER}| production | APOS, S	Ecoinvent
119	<0.0001	N,N-dimethylformamide {RER}| production | APOS, S	Ecoinvent
120	<0.0001	EDTA, ethylenediaminetetraacetic acid, at plant/RER S	Ecoinvent
121	<0.0001	Electricity, hydropower, at power plant/PL S	Ecoinvent
122	<0.0001	Ethoxylated alcohols, unspecified, at plant/RER S	Ecoinvent
123	<0.0001	Treatment, sewage, unpolluted, from residence, to wastewater treatment, class 2/CH S	Ecoinvent
124	<0.0001	Paraffin, at plant/RER S	Ecoinvent
125	<0.0001	Kraft paper, unbleached, at plant/RER S	Ecoinvent
126	<0.0001	Manganese, at regional storage/RER S	Ecoinvent
127	<0.0001	Polyacrylamide {GLO}| market for | APOS, S	Ecoinvent
128	<0.0001	Polyethylene, HDPE, granulate, at plant/RER S	Ecoinvent
129	<0.0001	Sodium dithionite, anhydrous, at plant/RER S	Ecoinvent
130	<0.0001	Sulphite, at plant/RER S	Ecoinvent
131	<0.0001	Sodium perborate, monohydrate, powder, at plant/RER S	Ecoinvent
132	<0.0001	Sodium perborate, tetrahydrate, powder, at plant/RER S	Ecoinvent
133	<0.0001	Sodium persulfate, at plant/GLO S	Ecoinvent
134	<0.0001	Sodium silicate, spray powder 80%, at plant/RER S	Ecoinvent
135	<0.0001	Tap water, at user/RER S	Ecoinvent
136	<0.0001	Zeolite, powder, at plant/RER S	Ecoinvent
137	<0.0001	Ethoxylated alcohols (AE11), palm oil, at plant/RER S	Ecoinvet
138	<0.0001	2-methyl-4-isothiazolin-3-one	MISTRA
139	<0.0001	5-chloro-2-methyl-4-isothiazoline-3-one	MISTRA
140	<0.0001	Acid (formic acid), average	MISTRA
141	<0.0001	Air emissions from 1 kg Acid (formic acid), average	MISTRA
142	<0.0001	Air emissions from 1 kg Detergent/Wetting agent, average	MISTRA

143	<0.0001	Air emissions from 1 kg Lubricant, average	MISTRA
144	<0.0001	Air emissions from 1 kg Sequestering agent, average	MISTRA
145	<0.0001	Alkyl ethoxylate	MISTRA
146	<0.0001	Antifoaming agent, average	MISTRA
147	<0.0001	Dimethyl siloxane, reaction product with silica	MISTRA
148	<0.0001	Sodium lauryl sulphate	MISTRA
149	<0.0001	Antireduction agent (H2O2), average	MISTRA
150	<0.0001	Base (alkali) (Na2CO3), average	MISTRA
151	<0.0001	Base (alkali) (NaOH), average	MISTRA
152	<0.0001	Black disperse dyestuff PA, BAT	MISTRA
153	<0.0001	Blue disperse dyestuff PA, BAT	MISTRA
154	<0.0001	Business trips for retail staff	MISTRA
155	<0.0001	Buttons, jacket	MISTRA
156	<0.0001	Carding for non woven process (CN)	MISTRA
157	<0.0001	Confectioning of jacket, per kg (mix)	MISTRA
158	<0.0001	MiFuFa electricity mix	MISTRA
159	<0.0001	Cotton thread, black 50 (mix)	MISTRA
160	<0.0001	Ring spinning to yarn, CO 300 dtex, average (mix)	MISTRA
161	<0.0001	Dyeing cotton/PES weave (mix)	MISTRA
162	<0.0001	Decalcifier ((NH4)2SO4), average	MISTRA
163	<0.0001	Detergent/Wetting agent, average	MISTRA
164	<0.0001	Oxirane, methyl-, polymer with oxirane, decyl ether	MISTRA
165	<0.0001	Polyacrylic acid, sodium salt	MISTRA
166	<0.0001	Sodium mono(2-ethylhexyl)estersulfate	MISTRA
167	<0.0001	Detergent/Wetting agent, BAT	MISTRA
168	<0.0001	Dispergent, average	MISTRA
169	<0.0001	Distribution & Retail of jacket	MISTRA
170	<0.0001	Transport of jacket to Sweden	MISTRA
171	<0.0001	Transport of jacket within Sweden	MISTRA
172	<0.0001	Electricity in the stores and offices	MISTRA

173	<0.0001	Transport of retail staff to stores	MISTRA
174	<0.0001	Packaging for jacket - store	MISTRA
175	<0.0001	District heating MiFuFa, Swedish average	MISTRA
176	<0.0001	Heat from waste, at municipal waste incineration plant with emissions	MISTRA
177	<0.0001	Dry spinning of elastane to fibres (mix)	MISTRA
178	<0.0001	Drying cotton/PES in stenter frame (mix)	MISTRA
179	<0.0001	Drying of jacket, LC	MISTRA
180	<0.0001	Drying PA6 in stenter frame (mix)	MISTRA
181	<0.0001	Dummy CaF2 (low radioactice)	MISTRA
182	<0.0001	Dummy Plutonium as residual product	MISTRA
183	<0.0001	Dummy Uranium depleted	MISTRA
184	<0.0001	DWR agent, average	MISTRA
185	<0.0001	Dyeing and drying PA6 weave black in beam dyeing machine, average (mix)	MISTRA
186	<0.0001	Sequestering agent, average	MISTRA
187	<0.0001	Wetting/Penetration agent (synthetic), average	MISTRA
188	<0.0001	Lubricant, average	MISTRA
189	<0.0001	Yellow disperse dyestuff PA, BAT	MISTRA
190	<0.0001	Soda (CaCO3), average	MISTRA
191	<0.0001	Dyeing and drying PA6 weave olive in beam dyeing machine, average (mix)	MISTRA
192	<0.0001	Dyeing and drying PES weave orange in beam dyeing machine, average (mix)	MISTRA
193	<0.0001	Red disperse dyestuff PES, average	MISTRA
194	<0.0001	Reducing agent, average	MISTRA
195	<0.0001	Softener, average	MISTRA
196	<0.0001	Electricity mix Bangladesh MiFuFa	MISTRA
197	<0.0001	End of life jacket	MISTRA
198	<0.0001	Filament DTY yarn, synthetic 100 dtex (mix)	MISTRA
199	<0.0001	Gussets in cotton/elastane tricot (mix)	MISTRA
200	<0.0001	Knitting yarn to fabric, 5 companies	MISTRA
201	<0.0001	Ironing of jacket, LC	MISTRA
202	<0.0001	Life cycle of jacket	MISTRA

203	<0.0001	Production of jacket (mix)	MISTRA
204	<0.0001	Use of jacket, 100 days	MISTRA
205	<0.0001	Polyacrylic amide acid, sodium salt	MISTRA
206	<0.0001	Melt spinning of PA6 to fibers (mix)	MISTRA
207	<0.0001	Melt spinning of PES to fibers (mix)	MISTRA
208	<0.0001	Needlepunching for non woven process (CN)	MISTRA
209	<0.0001	Non woven process (CN)	MISTRA
210	<0.0001	Opening and blending for non woven process (CN)	MISTRA
211	<0.0001	Padding for non woven process (CN)	MISTRA
212	<0.0001	Octadecanoic acid, reaction products with diethanolamine	MISTRA
213	<0.0001	Paper labels	MISTRA
214	<0.0001	Phosphonic acid, disodium salt	MISTRA
215	<0.0001	Weave PA black (mix)	MISTRA
216	<0.0001	Weave PA olive (mix)	MISTRA
217	<0.0001	Weave orange PES (mix)	MISTRA
218	<0.0001	Non woven PES for padding for jacket (mix)	MISTRA
219	<0.0001	Zippers jacket	MISTRA
220	<0.0001	Sodium disulphite	MISTRA
221	<0.0001	Ring spinning to yarn, synthetic 100 dtex (mix)	MISTRA
222	<0.0001	Transport of customers	MISTRA
223	<0.0001	Washing of jacket, LC	MISTRA
224	<0.0001	Wearing of jacket, LC	MISTRA
225	<0.0001	Washing detergent MiFuFa	MISTRA
226	<0.0001	Waste incineration of textile fraction in municipal solid waste (MSW), EU-27 S	MISTRA
227	<0.0001	Weaving to fabric 300 dtex (mix)	MISTRA
228	<0.0001	Weaving to fabric 150 dtex (mix)	MISTRA
229	<0.0001	Electricity mix Turkey MiFuFa System	MISTRA

Table 5S Results of Contribution Analysis After Hybridization

Contribution (kg CO2eq per Jacket)	Data Source	Process
0.2277	Ecoinvent	Electricity, medium voltage, at grid/CN S
0.1547	Ecoinvent	Tetrafluoroethylene, at plant/RER S
0.093	Ecoinvent	Nylon 6, at plant/RER S
0.0594	Ecoinvent	Electricity, natural gas, at power plant/UCTE S
0.0567	Ecoinvent	Transport, passenger car, medium size, petrol, EURO 5 {RoW}| transport, passenger car, medium size, petrol, EURO 5 | APOS, S
0.0477	CEDA	Other industrial machinery manufacturing
0.0453	CEDA	Other real estate
0.0325	CEDA	Management of companies and enterprises
0.0226	Ecoinvent	Compressed air, average generation, >30kW, 6 bar gauge, at compressor/RER S
0.0188	Ecoinvent	Polyethylene terephthalate, granulate, amorphous, at plant/RER S
0.0183	Ecoinvent	Transport, regular bus/CH S
0.0127	Ecoinvent	Transport, lorry 16-32t, EURO5/RER S
0.0115	CEDA	Advertising, public relations, and related services
0.0114	CEDA	Glass and glass product manufacturing
0.0096	CEDA	Manufacturing structures
0.009	CEDA	Nonresidential maintenance and repair
0.0086	CEDA	Architectural, engineering, and related services
0.0073	CEDA	Machine shops
0.0072	MISTRA	Electricity mix Turkey MiFuFa System
0.0069	CEDA	Light truck and utility vehicle manufacturing
0.0062	CEDA	Commercial structures, including farm structures
0.0059	Ecoinvent	Steel, low-alloyed, at plant/RER S
0.0056	CEDA	Semiconductor and related device manufacturing
0.0056	CEDA	Other fabricated metal manufacturing
0.0052	CEDA	Warehousing and storage
0.005	Ecoinvent	Electricity, low voltage, at grid/SE S
0.0048	Ecoinvent	Heat, light fuel oil, at boiler 10kW, non-modulating/CH S
0.0048	Ecoinvent	Steel product manufacturing, average metal working/RER S
0.0047	CEDA	Monetary authorities and depository credit intermediation

0.0047	Cotton Inc.	Cotton, based on Cotton Inc. data in GaBi
0.0045	Ecoinvent	Transport, transoceanic freight ship/OCE S
0.0042	CEDA	All other miscellaneous manufacturing
0.0042	CEDA	Services to buildings and dwellings
0.0037	CEDA	Nondepository credit intermediation and related activities
0.0037	Ecoinvent	Disposal, sludge from pulp and paper production, 25% water, to sanitary landfill/CH S
0.0036	CEDA	Custom computer programming services
0.0036	Ecoinvent	Disposal, sludge from pulp and paper production, 25% water, to sanitary landfill/CH EcoInvent System
0.0035	Ecoinvent	Packaging film, low density polyethylene {GLO}| market for | APOS, S
0.0034	CEDA	Wired telecommunications carriers
0.0033	CEDA	Insurance carriers
0.0032	CEDA	Other support services
0.003	CEDA	Lessors of nonfinancial intangible assets
0.003	CEDA	Legal services
0.0029	CEDA	Marketing research and all other miscellaneous professional, scientific, and technical services
0.0029	Ecoinvent	Aniline, at plant/RER S
0.0029	Ecoinvent	Waste incineration of fossil based textile fraction in municipal solid waste (MSW), SE
0.0026	CEDA	Data processing, hosting, and related services
0.0026	CEDA	Printed circuit assembly (electronic assembly) manufacturing
0.0026	Ecoinvet	Ethoxylated alcohols (AE3), petrochemical, at plant/RER S
0.0025	CEDA	Material handling equipment manufacturing
0.0024	CEDA	Business support services
0.0023	Ecoinvent	Electricity, oil, at power plant/UCTE S
0.0019	CEDA	Accounting, tax preparation, bookkeeping, and payroll services
0.0019	Ecoinvent	Electricity, hard coal, at power plant/CN S
0.0018	Ecoinvent	Formic acid, at plant/RER S
0.0017	CEDA	Commercial and industrial machinery and equipment repair and maintenance
0.0016	Ecoinvent	Solid unbleached board {GLO}| market for | APOS, S
0.0015	Ecoinvent	Brass, at plant/CH S

0.0015	Ecoinvent	Packaging film, LDPE, at plant/RER S
0.0015	Ecoinvent	Transport, lorry 7.5-16t, EURO5/RER S
0.0014	CEDA	Specialized design services
0.0014	Ecoinvent	Polyurethane, flexible foam, at plant/RER S
0.0013	Ecoinvent	Transport, passenger car, medium size, petrol, EURO 5 {RER}| transport, passenger car, medium size, petrol, EURO 5 | APOS, S
0.0012	CEDA	Employment services
0.0012	CEDA	Investigation and security services
0.0012	CEDA	Packaging machinery manufacturing
0.0012	Ecoinvent	Modified starch, at plant/RER S
0.001	Ecoinvent	Acrylic acid, at plant/RER S
0.001	Ecoinvent	Ethoxylated alcohols (AE7), petrochemical, at plant/RER S
0.0009	Ecoinvent	Electricity, high voltage, at grid/CN S
0.0009	Ecoinvent	Paper, recycling, with deinking, at plant/RER S
0.0006	Ecoinvent	Metal product manufacturing, average metal working/RER S
0.0006	Ecoinvent	Waste incineration of textile fraction of industrial waste - no credits
0.0006	Ecoinvent	Esterquat {RER}| treatment of tallow to | APOS, S
0.0006	Ecoinvent	Transport, lorry 16-32t, EURO3/RER S
0.0005	Ecoinvent	Cotton fibre {CN}| cotton production | APOS, S
0.0005	Ecoinvent	Lubricating oil, at plant/RER S
0.0004	Ecoinvent	Water, ultrapure, at plant/GLO S
0.0003	Ecoinvent	Lubricating oil, at plant/RER EcoInvent System
0.0003	Ecoinvent	Transport, lorry 3.5-7.5t, EURO5/RER S
0.0003	Ecoinvent	Zeolite, powder, at plant/RER S
0.0002	Ecoinvent	Acetic acid, without water, in 98% solution state {RER}| acetic acid production, product in 98% solution state | APOS, S
0.0002	Ecoinvent	Sodium hydroxide, 50% in H2O, production mix, at plant/RER S
0.0002	Ecoinvent	Hydrogen peroxide, 50% in H2O, at plant/RER S
0.0002	Ecoinvent	Calcium chloride, CaCl2, at plant/RER S
0.0002	Ecoinvent	Chemical, organic {GLO}| production | APOS, S
0.0002	Ecoinvent	Tap water {RoW}| market for | APOS, S
0.0002	Ecoinvent	Heat, natural gas, at boiler modulating <100kW/RER S
0.0002	Ecoinvent	Ethylene glycol monoethyl ether, at plant/RER S

0.0002	Ecoinvent	Treatment, sewage, unpolluted, from residence, to wastewater treatment, class 2/CH S
0.0002	Ecoinvent	Phosphoric acid, industrial grade, 85% in H2O, at plant/RER S
0.0002	Ecoinvent	Transport, regular bus {CH}| processing | APOS, S
0.0001	Ecoinvent	Acrylic dispersion, without water, in 65% solution state {RER}| acrylic dispersion production, product in 65% solution state | APOS, S
0.0001	Ecoinvent	Ethoxylated alcohol (AE7) {RER}| ethoxylated alcohol (AE7) production, petrochemical | APOS, S
0.0001	Ecoinvent	Diethanolamine, at plant/RER S
0.0001	Ecoinvent	Organophosphorus-compound, unspecified {RER}| production | APOS, S
0.0001	Ecoinvent	N,N-dimethylformamide {RER}| production | APOS, S
0.0001	Ecoinvent	Ethoxylated alcohols, unspecified, at plant/RER S
0.0001	Ecoinvent	Polyacrylamide {GLO}| market for | APOS, S
0.0001	Ecoinvent	Sodium dithionite, anhydrous, at plant/RER S
0.0001	Ecoinvent	Sodium perborate, monohydrate, powder, at plant/RER S
0.0001	Ecoinvent	Sodium perborate, tetrahydrate, powder, at plant/RER S
0.0001	Ecoinvent	Tap water, at user/RER S
0.0001	MISTRA	Washing detergent MiFuFa
0	CEDA	Noncomparable imports
0	Ecoinvent	Benzo[thia]diazole-compounds, at regional storehouse/RER S
0	Ecoinvent	Acrylic acid {RER}| production | APOS, S
0	Ecoinvent	Activated silica {GLO}| market for | APOS, S
0	Ecoinvent	Alkylbenzene sulfonate, linear, petrochemical {RER}| production | APOS, S
0	Ecoinvent	Ammonium sulphate, as N, at regional storehouse/RER S
0	Ecoinvent	Antimony, at refinery/CN S
0	Ecoinvent	Sodium carbonate from ammonium chloride production, at plant/GLO S
0	Ecoinvent	Transport, passenger, aircraft {RER}| intercontinental | APOS, S
0	Ecoinvent	Cobalt, at plant/GLO S
0	Ecoinvent	Corrugated board base paper, kraftliner, at plant/RER S
0	Ecoinvent	Maleic anhydride, at plant/RER S
0	Ecoinvent	Dimethylacetamide, at plant/GLO S
0	Ecoinvent	Dimethyl sulphate, at plant/RER S

0	Ecoinvent	Disposal, packaging cardboard, 19.6% water, to municipal incineration/CH S
0	Ecoinvent	Disposal, packaging paper, 13.7% water, to municipal incineration/CH S
0	Ecoinvent	Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH S
0	Ecoinvent	Disposal, textiles, soiled, 25% water, to municipal incineration/CH S
0	Ecoinvent	EDTA, ethylenediaminetetraacetic acid, at plant/RER S
0	Ecoinvent	Electricity, hydropower, at power plant/PL S
0	Ecoinvent	Paraffin, at plant/RER S
0	Ecoinvent	Kraft paper, unbleached, at plant/RER S
0	Ecoinvent	Manganese, at regional storage/RER S
0	Ecoinvent	Polyethylene, HDPE, granulate, at plant/RER S
0	Ecoinvent	Sulphite, at plant/RER S
0	Ecoinvent	Sodium persulfate, at plant/GLO S
0	Ecoinvent	Sodium silicate, spray powder 80%, at plant/RER S
0	Ecoinvet	Ethoxylated alcohols (AE11), palm oil, at plant/RER S
0	MISTRA	2-methyl-4-isothiazolin-3-one
0	MISTRA	5-chloro-2-methyl-4-isothiazoline-3-one
0	MISTRA	Acid (formic acid), average
0	MISTRA	Air emissions from 1 kg Acid (formic acid), average
0	MISTRA	Air emissions from 1 kg Detergent/Wetting agent, average
0	MISTRA	Air emissions from 1 kg Lubricant, average
0	MISTRA	Air emissions from 1 kg Sequestering agent, average
0	MISTRA	Alkyl ethoxylate
0	MISTRA	Antifoaming agent, average
0	MISTRA	Dimethyl siloxane, reaction product with silica
0	MISTRA	Sodium lauryl sulphate
0	MISTRA	Antireduction agent (H2O2), average
0	MISTRA	Base (alkali) (Na2CO3), average
0	MISTRA	Base (alkali) (NaOH), average
0	MISTRA	Black disperse dyestuff PA, BAT
0	MISTRA	Blue disperse dyestuff PA, BAT
0	MISTRA	Business trips for retail staff
0	MISTRA	Buttons, jacket
0	MISTRA	Carding for non woven process (CN)
0	MISTRA	Confectioning of jacket, per kg (mix)
0	MISTRA	MiFuFa electricity mix
0	MISTRA	Cotton thread, black 50 (mix)

0	MISTRA	Ring spinning to yarn, CO 300 dtex, average (mix)
0	MISTRA	Dyeing cotton/PES weave (mix)
0	MISTRA	Decalcifier ((NH4)2SO4), average
0	MISTRA	Detergent/Wetting agent, average
0	MISTRA	Oxirane, methyl-, polymer with oxirane, decyl ether
0	MISTRA	Polyacrylic acid, sodium salt
0	MISTRA	Sodium mono(2-ethylhexyl)estersulfate
0	MISTRA	Detergent/Wetting agent, BAT
0	MISTRA	Dispergent, average
0	MISTRA	Distribution & Retail of jacket
0	MISTRA	Transport of jacket to Sweden
0	MISTRA	Transport of jacket within Sweden
0	MISTRA	Electricity in the stores and offices
0	MISTRA	Transport of retail staff to stores
0	MISTRA	Packaging for jacket - store
0	MISTRA	District heating MiFuFa, Swedish average
0	MISTRA	Heat from waste, at municipal waste incineration plant with emissions
0	MISTRA	Dry spinning of elastane to fibres (mix)
0	MISTRA	Drying cotton/PES in stenter frame (mix)
0	MISTRA	Drying of jacket, LC
0	MISTRA	Drying PA6 in stenter frame (mix)
0	MISTRA	Dummy CaF2 (low radioactice)
0	MISTRA	Dummy Plutonium as residual product
0	MISTRA	Dummy Uranium depleted
0	MISTRA	DWR agent, average
0	MISTRA	Dyeing and drying PA6 weave black in beam dyeing machine, average (mix)
0	MISTRA	Sequestering agent, average
0	MISTRA	Wetting/Penetration agent (synthetic), average
0	MISTRA	Lubricant, average
0	MISTRA	Yellow disperse dyestuff PA, BAT
0	MISTRA	Soda (CaCO3), average
0	MISTRA	Dyeing and drying PA6 weave olive in beam dyeing machine, average (mix)
0	MISTRA	Dyeing and drying PES weave orange in beam dyeing machine, average (mix)
0	MISTRA	Red disperse dyestuff PES, average
0	MISTRA	Reducing agent, average
0	MISTRA	Softener, average
0	MISTRA	Electricity mix Bangladesh MiFuFa
0	MISTRA	End of life jacket
0	MISTRA	Filament DTY yarn, synthetic 100 dtex (mix)

0	MISTRA	Gussets in cotton/elastane tricot (mix)
0	MISTRA	Knitting yarn to fabric, 5 companies
0	MISTRA	Ironing of jacket, LC
0	MISTRA	Life cycle of jacket
0	MISTRA	Production of jacket (mix)
0	MISTRA	Use of jacket, 100 days
0	MISTRA	Polyacrylic amide acid, sodium salt
0	MISTRA	Melt spinning of PA6 to fibers (mix)
0	MISTRA	Melt spinning of PES to fibers (mix)
0	MISTRA	Needlepunching for non woven process (CN)
0	MISTRA	Non woven process (CN)
0	MISTRA	Opening and blending for non woven process (CN)
0	MISTRA	Padding for non woven process (CN)
0	MISTRA	Octadecanoic acid, reaction products with diethanolamine
0	MISTRA	Paper labels
0	MISTRA	Phosphonic acid, disodium salt
0	MISTRA	Weave PA black (mix)
0	MISTRA	Weave PA olive (mix)
0	MISTRA	Weave orange PES (mix)
0	MISTRA	Non woven PES for padding for jacket (mix)
0	MISTRA	Zippers jacket
0	MISTRA	Sodium disulphite
0	MISTRA	Ring spinning to yarn, synthetic 100 dtex (mix)
0	MISTRA	Transport of customers
0	MISTRA	Washing of jacket, LC
0	MISTRA	Wearing of jacket, LC
0	MISTRA	Waste incineration of textile fraction in municipal solid waste (MSW), EU-27 S
0	MISTRA	Weaving to fabric 300 dtex (mix)
0	MISTRA	Weaving to fabric 150 dtex (mix)
-0.0001	Ecoinvent	Peat, burned in power plant/NORDEL S
-0.0007	Ecoinvent	Heat, softwood chips from forest, at furnace 1000kW/CH S
-0.001	Ecoinvent	Heat, light fuel oil, at boiler 100kW condensing, non-modulating/CH EcoInvent System
-0.001	Ecoinvent	Heat, natural gas, at industrial furnace >100kW/RER S
-0.0018	Ecoinvent	Hard coal, burned in industrial furnace 1-10MW/RER S
-0.0047	Ecoinvent	Electricity, high voltage, at grid/SE S
-0.009	Ecoinvent	Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH S

Chapter Two: *Better to Stay Silent: Effect of Corporate Disclosure of Voluntary Chemical Risk Management on Consumer Behavior*

Introduction

Consumers are increasingly concerned about the safety of chemicals in the products they purchase.[1,2] With very few regulatory barriers around consumer products, thousands of chemicals are introduced into the market every day without the extensive toxicity and exposure assessments necessary to quantify the potential for risk.[3] Even without regulation, many companies are taking steps to identify and reduce the chemical risks in their products in an attempt to reduce business risks associated with future regulations and to avoid liabilities such as product recalls and PR crises if a risky chemical affects consumers.[4] Significant resources are being dedicated by companies to reduce these risks; however, these proactive actions are seldom communicated to consumers. Revealing these efforts to consumers would seemingly reflect well on the company's proactive management practices.

Yet companies remove chemicals quietly to make their products safer and rarely pass this information down to consumers. Take Nike, for example. In a report intended to educate suppliers that was released in 2018 the company describes actions taken to remove chemical risks from their products: "In Nike's supply chain, there are more than 3,000 chemicals…The Nike RSL [Restricted Substances List] restricts approximately 350 substances that have been regulated or voluntarily phased out of our manufacturing processes…While the Nike RSL tightly controls the most hazardous, opportunities exist to find better chemistry alternatives."[5] The 116 page report goes on to list all 350 chemicals that are restricted within Nike's supply chain, including descriptions of testing methods for each. Despite the fact that Nike has dedicated significant time and resources to the removal of these chemicals, these efforts have not been highlighted in consumer-facing communications. Nike's product or packaging labels do not indicate which chemicals have been intentionally removed, and Nike's public reports do not state when specific chemical risks were identified and removed from the products. Nike is one example, but many other companies have invested in programs to reduce chemical risks in their products, including Johnson and Johnson,[6] Levi Strauss,[7] and Target. A news article about Target's decision to expand its list of chemicals of concern to over 1000 chemicals across different product categories specifically calls out what is so puzzling about these changes, noting that Target "quietly posted a rather important update to its sustainable product standard addressing toxic chemicals".[8] Companies are taking the initiative to reduce chemical risks in their products, yet very few companies are communicating about the changes and improvements to their consumers except in cases, such as BPA, where the media has extensively covered the chemical risk.

Our analysis of this puzzle focuses on how consumer perceptions of company disclosure may be driving this observed firm behavior. An experimental survey design is employed to measure consumer behavior in response to company disclosure of proactive chemical risk management with and without the presence of media attention to that particular chemical risk. Robustness checks are used to further corroborate our findings through analysis of a second set of outcome variables and subgroup analysis. Lastly, two different spillover effects are presented as further observable implications: (1) the implications of one company's disclosure on consumers' attitudes towards another company selling similar products and (2) the implications of a company's disclosure about one product on consumer attitudes towards another product sold by that company.

Corporate Chemical Risk Management

Firms aim to increase the utility of their products in an attempt to increase consumers' willingness to purchase from them and to ensure competitive performance and financial success in the market.[9] Consumers' feelings towards a product or the company that makes it may be influenced by several different factors. Maslow's hierarchy of needs suggests that once the basic psychological needs (i.e. food, water, and sleep) are met, people begin to fulfill higher levels of needs, with safety being the next category they seek to satisfy.[10] Firms have strong incentives to be transparent about the safety of their products to maintain "social license to operate" and avoid sanctions through approval from external stakeholders, including consumers.[11,12,13]

Growing awareness of the health risks from chemicals in consumer products (BPA, flame retardants, etc.) has increased consumers' demand for information about the use of chemical ingredients in the products on the market.[1,2] On average, 5,500 substances are added to the Chemical Abstracts Services (CAS) Registry every day,[14] while only 50 substances are added to the Regulated Chemicals Listing (CHEMLIST®) each week.[15] Without the ability to rely on regulation to ensure the safety of chemical ingredients in products on the market, consumers want more information about the chemical risks in products they might purchase. In the absence of regulation, this valuable information can come from either the company itself or a public source like the media.

Companies control the ingredients in their products, and many are taking proactive measures to manage the risks associated with their chemical ingredients.[4] Corporate strategies to address these risks include the development of internal restricted substance lists, performance of tests and audits of suppliers, phasing out of chemicals or entire products, and evaluating chemical and product-related risks using assessment tools.[4] These proactive actions are driven by consumer demands for transparency as well as the threat of regulation and uncertainty about which chemicals will be regulated.[16] One company's ability to identify a risky chemical and remove it from their products may even be seen as a competitive advantage, as it reduces liabilities that could impact industry peers in the future.

If companies are taking these proactive measures to make their products safer, then why aren't they trying to get credit for their positive behavior? There are a few examples where companies explicitly promote actions to remove risky chemicals from their products (e.g., BPA, lead, and mercury), but these communications and product-labeling strategies are anomalies amongst the many chemical removals and replacements (e.g., triclosan, butylparaben, and dimethylfumurate) that companies are implementing to reduce risks in the absence of regulation. Take, for example, two chemical ingredients that have been removed from consumer products in recent years. The two chemicals pose relatively equal risks to consumers, but we observe very different patterns of initial disclosure by companies who removed each of these chemicals. One chemical is explicitly highlighted on product labels when it is not an ingredient, signaling to consumers that the product is safer than others without the label, and the other chemical is hardly mentioned in advertising or product-labeling. Sometimes the second chemical's removal is mentioned in small font on the back label of the product (usually on niche brands sold in organic or "natural" sections or specialty stores), but the disclosure is minimal. The different disclosure approaches suggest that companies expect different consumer responses to disclosure in each scenario, even if the risks are equal. Here we elaborate on this example – a comparison of bisphenol a (BPA) and triclosan – and discuss whether the media may play a differentiating role in consumer response to such disclosures.

The identification of BPA as a risky chemical and its removal from consumer products was done in a very public-facing manner. The adverse health effects of BPA exposure as an endocrine disruptor have been studied since the late 1990s. While there is debate about the risks posed to humans based on current exposure levels in existing product categories, animal testing has demonstrated negative health effects with low-dose exposure.[17-20] Despite the fact that BPA is only officially banned from baby bottles and sippy cups, many companies now advertise "BPA-free" plastic products of all kinds. The "BPA-free" disclosure movement came in response to major criticisms of the chemical industry. At the forefront were media claims that the FDA ruling on BPA in other product categories ignored many published scientific health studies and was largely driven by two studies that were both funded by a chemical industry trade group.[21] General Mills,[22] ConAgra, Eden Foods, Hain Celestial Group, and Heinz were just a few of the companies that began promoting their "BPA free" products in response to these concerns raised in the media.

Triclosan poses similar risk in consumer products as BPA[23,24] and has also been removed from many large-brand products, yet "triclosan-free" labels or similar promotions of this chemical's removal are not common in consumer products. Research findings on the negative health effects of triclosan in soaps and body washes are similar to those of BPA, with studies demonstrating that exposure to triclosan alters hormone regulation in animals, may contribute to the development of antibiotic-resistant germs, and may be harmful to the immune system.[25-27] The amount of publicly available information on the risks of triclosan is comparable to that of BPA. A Google Scholar search of "triclosan health effects" (date range 2010-2018) performed on April 27, 2018 returned 17,000 results, a number comparable to the 17,900 results when "bisphenol a health effects" was searched at the same time within the same date range. Several major companies, including Colgate-Palmolive, Johnson & Johnson, Procter & Gamble, Clearasil, and Unilever have reformulated to remove triclosan from at least some of their product lines.[28] An Amazon.com search for "BPA free" products resulted in over 100,000 hits, while "triclosan free" generated about 2,000 results. Given the number of major companies to take steps to remove triclosan, we would expect these numbers to be more comparable if the labeling and communication strategies were similar.

One major difference between the cases of triclosan and BPA is the media environment. Google News searches resulted in 44,100 media hits for "BPA health risks" and only 5,130 for "triclosan health risks". This difference is drastic and may help to explain why companies disclose in some scenarios and not others. Firms may communicate about or promote these removals only once a chemical risk has gotten significant attention in the media. These observations suggest that firms expect different reactions from consumers depending on the media environment; therefore, we are interested in understanding the role of the consumer response in driving firm decisions to disclose chemical risk management practices. We investigate the consumer response to corporate communications about removal of chemicals from products – both with and without prior media attention – to understand how consumer behavior under different conditions may influence companies' decisions to promote proactive chemical risk management.

Hypotheses

Broadly, the observed patterns of company communication suggest that consumers may respond differently to company disclosure depending on whether the media has already made them aware of the risk. Media disclosure is likely to reduce trust in companies that produce a product that could contain the risky chemical, which may be mitigated by company disclosure of actions they have taken to remove the chemical. On the other hand, when a company proactively discloses removal of a chemical, the company's identification of the risk may be interpreted by consumers as an admission of guilt, eliciting a negative response that may mask any effect of the positive behavior to proactively remove a risky chemical. In the following, we identify the mechanisms and expectations that lead to three hypotheses displayed in Figure 1.

First, media disclosure of a chemical risk will reduce willingness to purchase from companies that produced products with that chemical. A wrongdoing that deviates from stakeholder expectations can violate consumers' trust and attract significant attention to companies that may be at fault.[29,30] When consumers are made aware of a chemical risk in the products they purchase, and formerly believed those products to be safe, this negative violation of expectations can create cognitive dissonance and generate negative emotional responses.[31-33] When the media announces this risk, consumers may assign this negativity broadly to any products that could contain the chemical under question and any companies that make those types of products. This leads to our first hypothesis:

H1: When a chemical risk in consumer products is identified in the media, consumer willingness to purchase products in that category will decrease.

This may seem obvious and oversimplified, but establishing this effect decouples the effect of media attention from the company's decision whether or not to disclose. In the following hypotheses we can compare the consumer response to disclosure under each scenario with the baseline media effect established in this first hypothesis.

Second, company disclosure of actions taken to mitigate the risk will reduce the negative effect of media disclosure. When media attention has been given to a chemical risk, companies may choose to respond by either disclosing their positive behavior to remove the chemical or by beginning to label their products as "free of" that chemical. These communications signal to consumers that the company has taken technical actions to address the issue raised in the media, i.e. reformulating the product to remove the risky chemical. Technical actions are expected to lessen the negative response from consumers, as they align with current media portrayals and consumer perceptions of the company and can be interpreted as positive actions to address a now established problem.[34] Issuing a response that does not describe specific actions to remove the chemical, on the other hand, could potentially exacerbate the negative consumer response.[31] We already hypothesized that media attention to a chemical risk in consumer products would elicit a negative consumer response. A generic statement from the company that does not address the media-identified chemical risk could be viewed as deceitful, confusing, or even an admission of guilt.[31,35] We anticipate that corporate communications about positive technical actions will be well received in light of the media attention to a chemical risk in consumer products; however, we do not expect this effect to be stronger than the effect of the media coverage, since a negative event can destroy trust more than an equally positive event can instill trust.[36] This leads to our second hypothesis:

> *H2: When a chemical risk in consumer products is identified in the media, a company's disclosure of positive behavior to remove the risky chemical will lessen the negative effect on consumer willingness to purchase products in that category.*

Third, when companies proactively disclose the removal of chemical risks, consumers will reduce their willingness to purchase from those companies, resulting in incentives not to proactively disclose. Observable corporate actions in examples like BPA are consistent with this hypothesis, but we know little about how consumer response influences corporate behavior in cases like triclosan with little media attention. Even in the absence of regulation and media attention, consumer product companies are proactively testing, analyzing and mitigating risks from chemical ingredients in their products.[4] Their actions may preempt both regulation and media coverage, yet we rarely see examples where they disclose these actions. Here we consider how consumer behavior may influence a company's willingness to communicate proactively about these positive actions. The information communicated when a company proactively discloses is no different than what is communicated when the media is identifying the risk; only the source of this information is different. Consumers may respond differently depending on the information source, since their expectations about the information that different sources will share and their degree of trust in the informant could be different. Trust in the media regarding chemical risk in food, for example, is higher than trust in corporations, as public-oriented sources like consumer associates and government agencies are perceived as more trustworthy than groups with vested interests.[37] If we expect the trust in the company to be low, then any information they communicate about good behavior to remove risky chemicals may be seen as manipulative or driven by ulterior motives.

If a company does wish to communicate about proactive chemical risk management, they need to share two pieces of information: (1) an announcement of the discovery of a previously unknown risk and (2) an explanation of how that risk is being mitigated (i.e. removed or replaced). When a company itself identifies the risk, it is explicitly admitting to the prior wrongdoing, violating the consumer's expectation that its products are safe. The information shared by the company about actions to proactively remove the risky chemical may be lost in a consumer focus on the prior risky behavior. We expect the positive action to remove the risky chemical to be outweighed by this negative effect on consumer behavior. This leads to our final hypothesis:

> *H3: A company's proactive disclosure of positive behavior to identify and remove a risky chemical from their consumer products will negatively influence consumers' willingness to purchase those products.*

If consumer trust in the company as an information source is low, then we may observe no effect at all, since consumers will struggle with whether to believe and act upon both the positive and negative information disclosed. Given that companies have not typically been the source to communicate about chemical risks, consumers with low trust in the organization may perceive this type of disclosure to be manipulative or driven by ulterior motives, and the message may be ignored.

Figure 1 displays the main hypotheses, illustrating the significance of the media context in the influence of company disclosure on consumer behavior.

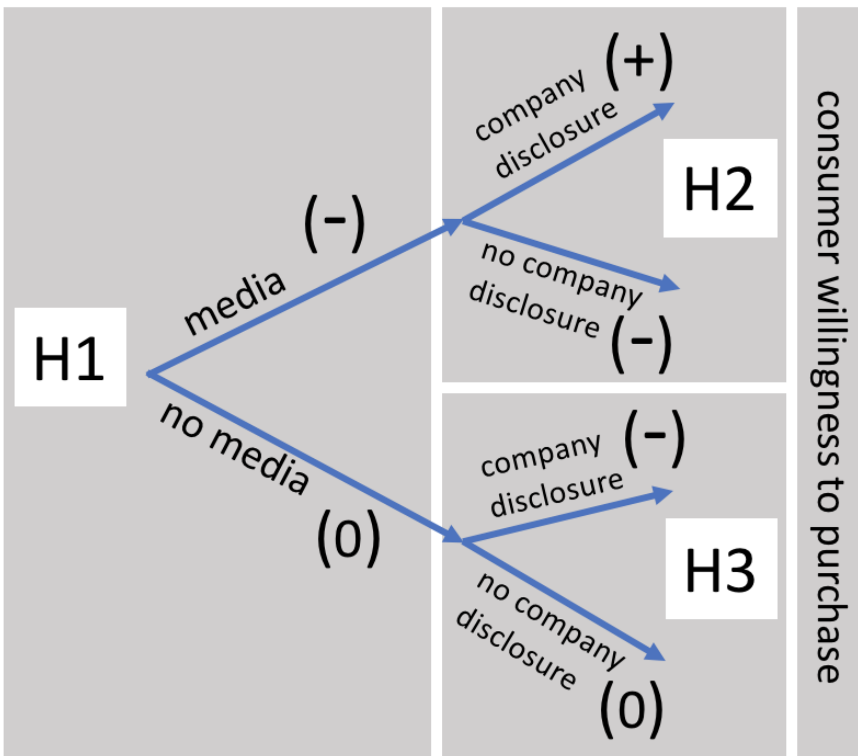

Figure 1. Hypotheses about the consequences of media and company disclosure about chemical risks in consumer products on consumer behavior (willingness to purchase).

Data and Methods

Survey recruitment and data collection were performed using Amazon's Mechanical Turk (MTurk).[38] MTurk is a crowdsourcing internet marketplace in which respondents could be compensated by completing a survey. In order to participate, respondents needed to be at least 18 years of age and English-speaking. The survey was posted on MTurk for five days, from 02/20/18 to 02/24/18. The sample was representative of the adult US population on gender, political party affiliation, education level and household income, but it over represents the younger demographic. A summary of participant (n=1779) demographics is included in the Supplemental Information. To improve the representativeness of our sample, specifically with respect to age distribution, we employed weighting to ensure that our results are more generalizable for the US population.

Survey respondents were divided into four groups based on a full factorial 2 X 2 (media announcement or not X company disclosure or not) design, with one of the messages being the Control (no media announcement, no company disclosure). Figure 2 displays this study design. The fictitious company used in the Treatment was called "Dssrttn Inc." In all three Treatments, phthalates were highlighted as a chemical in personal care products, among other product categories, that poses significant health risks. Phthalates were chosen as the case study for two reasons. First, the health risks of phthalates are relatively well known, with 17,200 Google Scholar results for "phthalates health risks" published between 2010 and 2018 (a similar number to both BPA and triclosan). Second, the media has not covered phthalates very extensively (Google Media hits = 10,900, which is much closer to the triclosan number than to the BPA number), so media disclosure can be manipulated.

Survey participants received one of four sets of information to read before answering the questions. They were each introduced to a fictitious company named Dssrttn Inc. that sells a variety of consumer products that are common in most US households. This description of Dssrttn Inc. was consistent across all Treatments. To measure the influence of media attention to a chemical risk, Treatment groups 2 and 3 were provided with an additional piece of information. Before being introduced to Dssrttn Inc., they were given a real excerpt from the New York Times "Well" Blog, describing the health risks of phthalates specifically in personal care products, among other product categories: "…prenatal exposure [of phthalates] has been linked in studies to problems with attention and intellectual deficits…they are still widely used in all kinds of products, from food packaging to personal care products…" ("A Call for Action on Toxic Chemicals" - July 1, 2016).

Following the blog excerpt (for Treatment groups 2 and 3) and the company description, each participant then read a statement issued by Dssrttn Inc. The participants in the "No Company Disclosure" groups (Control and Treatment 3) read a statement in which Dssrttn Inc. generically described efforts to minimize health risks and environmental risks of its products, focusing on positive and broad statements about the company's actions and goal to introduce new products that meet consumer needs. The participants in the "Company Disclosure" groups (Treatment 1 and Treatment 2) read a statement from Dssrttn Inc. with very similar language but that also included a very specific action to proactively manage a chemical risk: "This past year, we lab-tested chemical ingredients from our suppliers and decided to remove all phthalate ingredients from our shower and bath product lines, now making all of our products safer than ever before." After receiving the content described above, participants in all groups were asked a series of questions.

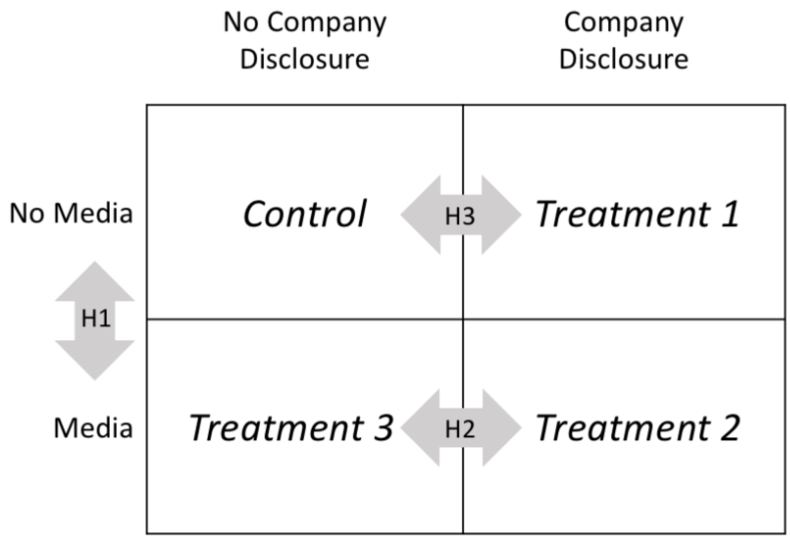

Figure 2. Setup of Control and Treatments within the 2x2 factorial study design.

The primary dependent variable measured in the study was willingness to purchase (WtP). Trust in the company was measured as a secondary outcome variable and will be discussed further within the robustness check after the main results are presented. After receiving their Treatment or Control message, respondents were asked to indicate their WtP bath products from Dssrttn Inc., as well as their trust in Dssrttn Inc. Following the questions about WtP and trust, a manipulation check was included in the survey to confirm that the Treatments were effective and that respondents absorbed the intended information. Respondents were asked how risky they believed phthalates to be and whether they believed phthalates were present in bath products from Dssrttn Inc. Finally, respondents were asked several demographic questions: age, gender, party affiliation, income and education level.

We included several additional questions in the survey to measure the spillover effects of the Treatments to bath products from other companies and different products from Dssrttn Inc. These spillover effects will be presented and discussed in the "Additional Observable Implications" section of our paper. After the initial questions about Dssrttn Inc.'s bath products, respondents received the same questions about WtP and trust in these two other scenarios. Manipulation checks were included for both of these spillover measures as well, with respondents being asked separately if they believe phthalates are in bath products from the second company and other products from Dssrttn In. The full survey instrument (Control, Treatments, and questions) is included in the Supplemental Information.

Results

The results for all three hypotheses are displayed in Figure 3. We first analyzed the effect of a media identification of a chemical risk in consumer products on the primary dependent variable, consumer WtP. We did so by employing an ordinal logistic regression while controlling for all other covariates in our study. To evaluate the influence of media attention, we compared pooled WtP from the two groups that did not receive a media announcement in their Treatment (Control and Treatment 1) to the two groups who read the *New York Times* blog post about the risks of phthalates in consumers products (Treatment 2 and Treatment 3). Consistent with *H1*, the pooled Treatment effect of the media communication was negative for consumer WtP (-0.688, $p<0.001$), establishing that media attention to a chemical risk in consumer products generates a negative response in consumer behavior towards that company's products. The difference in WtP when media attention does or does not exist is portrayed in Figure 3 through a comparison of the two shaded areas. The upper shaded area represents the WtP amongst the Control and Treatment 1 groups who did not receive media Treatments, and the lower shaded area represents the WtP amongst the groups that did read the blog post about phthalates (Treatments 2 and 3).

We then analyzed the effect of a company disclosure in response to a media announcement in which they describe actions to remove the risky chemical from their products. We compare WtP when Dssrttn Inc. either communicates that they are removing phthalates from their products (Treatment 2) or maintains a generic positive statement about the company (Treatment 3). In comparing these two potential responses portrayed in the lower shaded area on Figure 1, the disclosure of technical action to remove the chemical risk had a positive effect on consumer WtP (0.689, $p<0.001$) compared to the effect of a generic positive statement on consumer WtP from Dssrttn Inc. This result is consistent with *H2*, demonstrating that after media attention has highlighted a chemical risk, consumers respond better to companies who disclose positive behavior to remove that chemical than to those who do not highlight specific responses.

Next, we evaluated whether consumers responded well to companies who shared details on this good behavior without the media first identifying the chemical risk (H3). Here we compare consumer WtP bath products from Dssrttn Inc. when Dssrttn Inc. only issues a generic positive statement about the company (Control) and when Dssrttn Inc. communicates about their identification and removal of a risky chemical (phthalates) from their products (Treatment 1). Consumer response to this proactive disclosure was slightly positive and insignificant for WtP (0.021, $p=0.866$), as portrayed in the upper shaded area in Figure 1. The lack of significant effect on consumer behavior suggests that consumers struggled to interpret this self-reported positive company behavior. This observed result, or lack thereof, will be analyzed further in the following section, but first we present results for our second outcome variable to add validity to the initial findings.

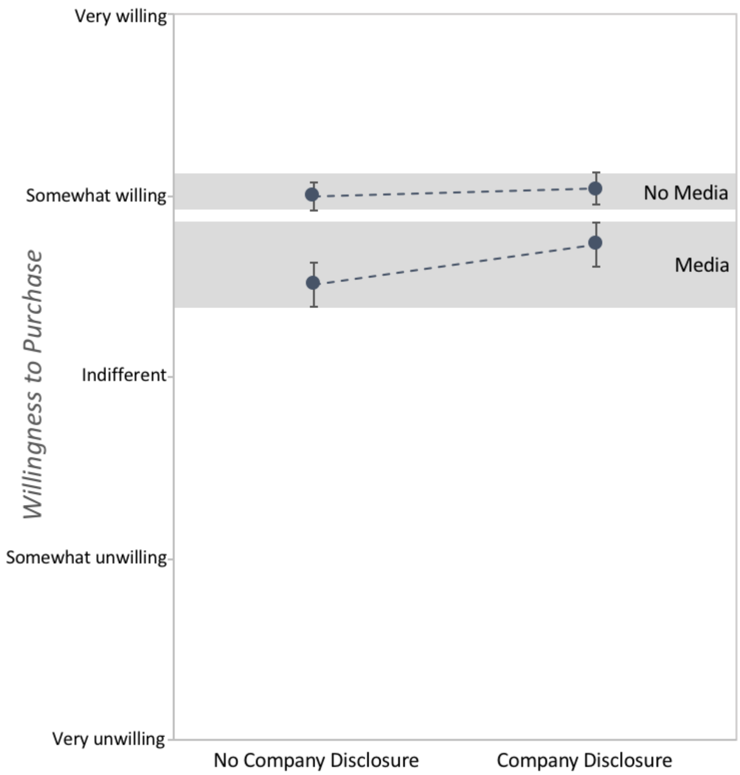

Figure 3. Results for main effects on primary outcome variable: consumer willingness to purchase. Lower shading includes data from Treatments 2 and 3 in which respondents were exposed to a media announcement; upper shading includes data from the Control and Treatment 1 in which no media announcement was presented to the participants. Error bars represent 95% confidence intervals.

As a robustness check, we analyze the results for a second outcome variable, trust in the company, under all of the same conditions. We expect that consumer response to the media and/or a corporate communication will be reflected in both their feelings towards the products and towards the companies producing them. If our results are robust, then we should observe similar effects on trust in Dssrttn Inc. as we do on WtP their bath products. Table 1 displays the results for both outcome variables in each of the three analyses. The effects and standard errors for WtP and trust are similar for all three cases, strengthening the validity of our results.

Table 1. Robustness check demonstrating consistency between results for primary (WtP) and secondary (trust) outcome variables (indicates p<0.001)*

Measure	WtP		Trust	
	effect	*std error*	*effect*	*std error*
Pooled Treatment effect of media (H1)	-0.688*	0.090	-0.671*	0.090
Effect of corporate disclosure after media attention (H2)	0.689*	0.134	0.532*	0.133
Effect of corporate disclosure w/out media attention (H3)	0.021	0.127	0.094	0.122

The Role of Trust

Returning to the results for the third hypothesis, we further investigate why consumers respond neither positively nor negatively to the company's proactive disclosure of actions to reduce chemical risks. Lack of consumer trust in companies may help to explain why no significant effect on WtP was observed when Dssrttn disclosed a chemical removal in the absence of media attention. Participants in Treatments 1 and 2 were told that Dssrttn Inc. removed phthalates from their bath and shower products in the company's statement about their actions. When asked later in the survey if they believed phthalates were in Dssrttn's bath and shower products, the manipulation check revealed that 45% of respondents in these groups believed phthalates were indeed in Dssrttn's bath and shower products. There are two probable explanations for this outcome: either (1) respondents did not carefully read through their Treatment and did not absorb the content or (2) respondents did not trust that Dssrttn Inc. was being truthful about their actions. To evaluate the possibility of this second explanation, we analyzed the relationship between consumer trust in Dssrttn Inc. and their response to the manipulation check. This analysis only included a subset of the data, since only Treatments 1 and 2 included a disclosure from Dssrttn Inc. stating that they had removed phthalates from their bath and shower products. (In the Control and Treatment 3 the company only issued a generic statement, so the survey respondents are not expected to know whether phthalates are in the products or not.) Results of a regression demonstrate a positive correlation (2.55, $p<0.001$) between respondents' ability to correctly respond to the manipulation check and trust in Dssrttn Inc. The 55% who responded that phthalates were not in Dssrttn Inc.'s products, as stated in their Treatment, had higher trust in Dssrttn Inc. Respondents with lower trust in the company may have been more hesitant to accept the corporate statement as fact. This may help explain the unclear consumer response to the company's communications about both the risk identification and the actions to remove the chemical.

By dissecting the study sample based on their reported trust in the company, we can further analyze the degree to which trust in the company influences the consumer response. To do this we separated the sample into two groups: high trust and low trust. The high trust group included respondents who reported their degree of trust in Dssrttn Inc. as "a moderate amount", "a lot" or "a great deal", regardless of their treatment group, and the low trust group as those who reported their degree of trust in the company as "not at all" or "a little". Comparing results for each hypothesis between the two groups, we observe that only the low trust group is significantly influenced by the media (H1 effect size = -0.974, $p<0.001$) and only the high trust group is significantly influence by the company's disclosure in response to media attention (H2 effect size = 0.696, $p<0.001$). This further corroborates the notion that an individual's trust in the company, and possibly in companies in general, will affect their response to the media and to company disclosure. In this instance, we might interpret the lack of effect of media attention on the high trust group to mean that their trust in the company is stronger than it is in the media. Additionally, the H2 results in this subgroup analysis indicate that the high trust group responds well to the company's response to the media, but the low trust group does not, suggesting that the low trust group may place more trust in public-oriented sources like the media than in the company. These results point to company trust as a key factor in the consumer response to information from various sources.

We can further validate the findings through another subgroup analysis. Conservatives (Republicans) have a higher baseline trust in companies than liberals (Democrats).[39] If the subgroup analysis is consistent with our other results, we should observe higher WtP and trust from Republicans than from Democrats across all Treatments. As expected, conservatives (Republicans) did on average have higher WtP and trust than liberals (Democrats) across all Treatments (0.268, $p=0.017$ and 0.289, $p=0.009$, respectively). An interesting outcome of our subgroup analysis was that the largest difference in WtP between Republicans and Democrats occurred when media attention was given to phthalates and the company only issued a generic positive statement. Figure 4 demonstrates this outcome, highlighting that Republican WtP was relatively similar to that of Democrats in all Treatments other than Treatment 1 (media, no company disclosure). Democrats punished companies for not responding with disclosure of technical actions when the media identified a chemical risk, but Republicans' behavior did not change significantly.

As expected, Republican WtP was overall higher than Democrats, but our analysis demonstrates that the difference is largely driven by just one scenario. We observe that Republicans are just as willing to purchase products from the company when they do not address chemical concerns raised in the media as when they do disclose technical actions to remove the chemical. The higher baseline trust of Republicans in companies helps to explain this outcome, further corroborating the role of trust in the consumer response to proactive company disclosure. Trust in source may be relevant from another perspective as well. Democrats may place more trust in media and thus their behavior is influenced by the media's announcement of a risk; however, Republicans may dismiss any media statements and consequently do not change their behavior, as demonstrated in Figure 4.

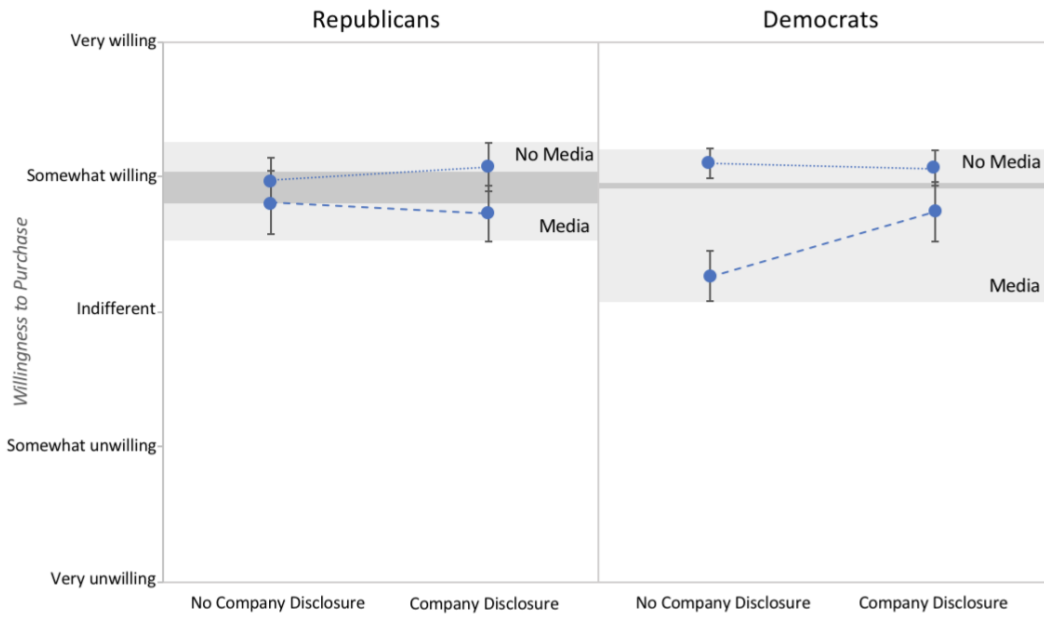

Figure 4. Reported WtP of Democrats vs. Republicans in response to company disclosure. Error bars represent 95% confidence intervals.

Additional Observable Implications

The reputation of an entire industry can sometimes be stronger than that of an individual firm, making it such that an event related to one company can reflect poorly on others as well.[40-42] On the one hand, a wrongdoing by one firm may elicit a negative response from consumers that is directed to company peers as well; on the other hand, a firm that responds well to a negative incident may be able to distinguish itself positively from other firms in the eyes of the consumer.[34] For these reasons, we expect consumer response to a second firm in the same industry to be dependent on the behavior of the more vocal firm. Media attention to the chemical risk is expected to elicit a negative consumer response equally across firms. If one company responds well by disclosing positive actions to remove that risk, it could reflect badly on another firm that did not respond at all if consumers draw a comparison between the two firms' behaviors. On the other hand, if the firm has not taken steps to remove the chemical and has no concrete action to disclose, there may be an incentive to stay silent rather than issuing a broad positive statement. Consumers may respond negatively to a company who responds with a generic positive statement, since it could draw attention to the fact that no real action has been taken to remove the risky chemical.

In the context of just one company, spillover effects to other products may be observed. Consumers may interpret the behavior of a company in one scenario to be representative of their entire management performance and behavior. A wrongdoing in one product category may elicit a negative emotional response from consumers that then informs their perceptions of all the company's products. On the other hand, if a company can improve consumers' perceptions through disclosing positive technical action around one product, the improved consumer response may spill over to the company's other product areas.

Figure 5 presents a comparison of how Dssrttn's decision to disclose influences the public's WtP both other products at Dssrttn and the same type of product (bath products) from another company. While consumer WtP increased when Dssrttn Inc, responded to the media with disclosure of concrete positive action, a negative effect on WtP from the second company is observed in this Treatment (-0.256, p=0.055). Dssrttn Inc.'s positive action in the eyes of the consumer likely draws attention to the lack of action from other companies and results in a more negative consumer response.

Results presented in Figure 5 also indicate that the effects of media and company disclosure around one product spill over to other products made by the same company. When Dssrttn Inc. discloses action to remove phthalates from the company's bath products in light of media attention to the chemical risk, there is a positive effect on consumer WtP these products (0.689, p<0.001). The positive effect of this disclosure on consumer behavior is observed to a lesser degree in consumer WtP for other products from Dssrttn (0.383, p=0.004). Even though Dssrttn Inc. does not explicitly mention good behavior in other product categories, their disclosure of positive behavior in one area may be rewarded in consumer WtP products across their product portfolio.

When companies proactively disclose actions to remove phthalates from bath and shower products, there is no significant effect on consumer behavior. The confusion amongst consumers – possibly due to lack of trust in the company – is also observed for other products sold by Dssrttn Inc. that they have not discussed in communications. This finding further corroborates the strong tie between consumer perceptions of a product and the parent company. Figure 5 demonstrates the similarities between effects observed for Dssrttn Inc.'s bath products and another product sold by Dssrttn. While Dssrttn's attention to one product may raise awareness that a competitor is not addressing the issue, it does not reflect poorly on Dssrttn's other products. The right-hand side of Figure 5 illustrates that the effects of disclosure by Dssrttn Inc. about its bath products (blue marker) spills over positively to other products made within the same company (orange marker) and negatively to another company selling the same types of products (grey marker).

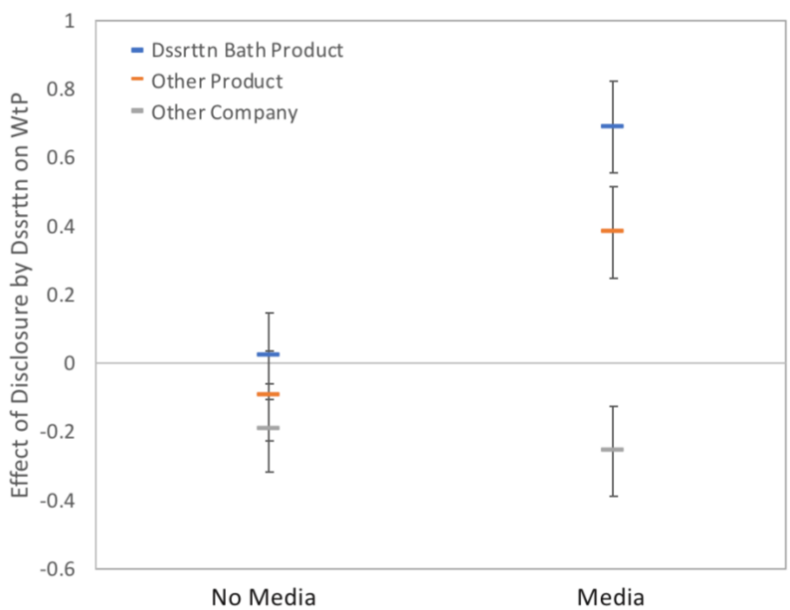

Figure 5. Spillover effects on consumer WtP of a company's disclosure around one product to that of another product at the same company ("Other Product") and the same type of product sold at a different company ("Other Company"). Error bars represent standard errors.

The effect of the media attention to a chemical risk should be equal across all companies and products mentioned in the *New York Times* blog post: "they [phthalates] are still widely used in all kinds of products, from food packaging to personal care products and building materials." While this is generally true in the study results, the pooled Treatment effect of the media coverage of a chemical risk on WtP was much weaker for the other company than for Dssrttn Inc. (-0.668, $p<0.001$ and -0.368, $p<0.001$ for Dssrttn and another company, respectively). This begs the question of whether companies may benefit from staying silent in the wake of negative industry-wide media attention. We compared WtP results for Dssrttn Inc. and the second company in the two Treatments where Dssrttn Inc. issued a generic positive statement and the other company said nothing (Control and Treatment 3). In both scenarios (with and without media attention) a chi-squared test revealed that the results were significantly different for Dssrttn Inc. compared to the second company, and the consumer WtP was slightly higher for Dssrttn Inc. This suggests that consumers respond better when a company issues a positive statement, even a ceremonial one, as opposed to staying silent in the wake of an industry-wide wrongdoing. Figure 6 demonstrates this finding, highlighting that consumer WtP favored Dssrttn over the other company in all scenarios because the lighter colored data points representing Dssrttn Inc. were all higher in WtP than the darker colored data representing the second company on the plot. If staying silent was advantageous, then the WtP for the other company would have exceeded that of Dssrttn Inc. in the scenarios where Dssrttn issues a generic positive statement ("no disclosure" in Figure 6), especially in light of media attention.

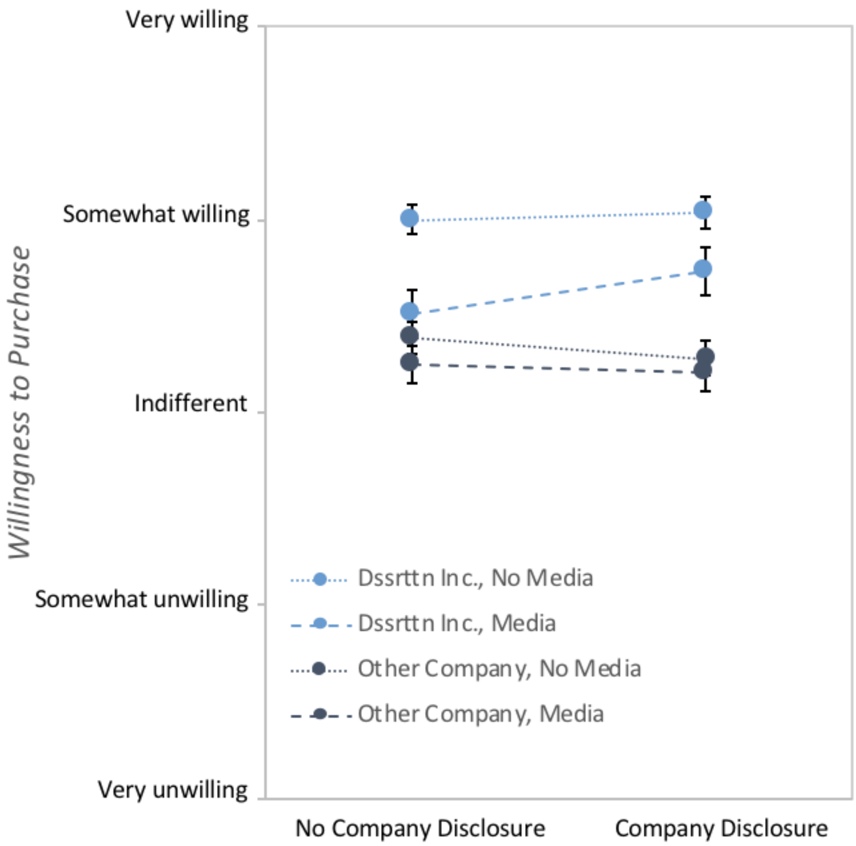

Figure 6. Comparison of effects of disclosure on consumer WtP for Dssrttn Inc. versus another company. The second company issued no statement at all, while "No Company Disclosure" for Dssrttn Inc. describes the scenario where Dssrttn issued a generic positive statement. Error bars represent 95% confidence intervals.

Discussion

This study examined consumer behavior in response to firm disclosure of chemical risk management practices in the presence and absence of the media. There is evidence that firms are taking proactive measures to reduce these risks in consumer products,[4] yet there is little evidence of firms disclosing this good behavior on product labels or in public press releases unless the media has already drawn attention to the specific chemical risk. This study shows that companies stay quiet even when they undertake positive actions because they do not benefit from such pre-emptive disclosures. Instead, they can mostly erase negative media exposure by revealing with specificity that they have responded once the media has revealed chemical risk.

This begs the question of why firms then choose not to proactively disclose, since it appears they have nothing to lose and possibly a little bit to gain. Trust may be a key factor in this outcome, since we observe a correlation between Trust in Dssrttn Inc, and respondents' belief that the company actually took action to remove the risky chemical. If the consumers do not trust the company, then they may be skeptical of any communications and perceive them to be manipulative or driven by ulterior motives. For consumers who perceive companies to only prioritize the bottom line, positive and proactive disclosure about voluntary actions to identify and remove a chemical risk may be confusing, as it does not align with their existing expectations about the firm's behavior.

An additional explanation for why firms might not disclose, even when the consumer response could be neutral or even positive, is the attention it may draw from other sources. When the media presents the chemical risk, our study indicates that the consumer response is decisively negative and leaves companies in a reactionary position where they can only lessen the damage by disclosing good behavior to remove the chemical. A proactive and voluntary disclosure by one firm may elicit media attention that selectively discusses the now known risk, regardless of whether the company is credited with the discovery or with the proactive response to mitigate the risk. Disclosure may put firms in a vulnerable position in this regard, especially since consumer trust in the media is higher than that in companies. It was not in the scope of our study, but further research should investigate the timing of these communications and whether proactive disclosure can effectively shield firms from the negative response once the risk gains media attention. Or must firms save their disclosure of positive actions until after media disclosure to benefit?

In the absence of regulation, firms may turn to industry associations or other information intermediaries to communicate about these voluntary behaviors on behalf of the individual companies. Certifications and collective product-labelling strategies may be better received by consumers than when the source is an individual firm. Future research should explore the role of third parties in how corporate communications about proactive chemical risk management influence consumer behavior.

Consumers would be better off if they had more information about which products are safe and what ingredients to look for on product labels, but companies often make these improvements quietly without drawing any attention to specific actions. Consumers' own behavior places companies that are investing in proactive measures to mitigate the risks of chemicals in their products in a lose-lose situation where they do not gain from disclosure of their proactive behavior and can only reduce the negative effect if the media draws attention to the risky chemical.

References

(1) Schmidt, C. W. Face to Face with Toy Safety: Understanding an Unexpected Threat. *Environmental Health Perspectives*. **2008**, 116(2), A70-A76.

(2) Betts, K. S. New Thinking on Flame Retardants. *Environmental Health Perspectives*. **2008**, 116(5), A210-A213.

(3) https://www.cas.org/content/chemical-substances/cas-registry-100-millionth-fun-facts

(4) Scruggs, C. E.; Ortolano, L. Creating safer consumer products: the information challenges companies face. *Environmental Science & Policy*. **2011**, 14, 605-614.

(5) Nike Chemistry Playbook & Restricted Substances List 2018. Accessed at https://about.nike.com/pages/chemistry-restricted-substances-list

(6) Johnson & Johnson, Principles for Safe Use of Chemicals in Products. **2017**. Accessed at https://www.jnj.com/_document/johnson-johnson-principles-for-safe-use-of-chemicals-in-products?id=0000015c-833b-d751-a55d-bfff76f60000

(7) Levi Strauss. Restricted Substances List. **2014**. Accessed at http://levistrauss.com/wp-content/uploads/2014/09/July-2014-RSL-English.pdf

(8) https://saferchemicals.org/2015/09/28/target-takes-another-significant-step-to-address-toxic-chemicals/

(9) Marshall, Alfred. *Principles of Economics. An introductory volume* (8th ed.). **1920**, London: Macmillan.

(10) Maslow, A. H. A theory of human motivation. *Psychological Review*. **1943**, 50(4): 370-396.

(11) Suchman, M. C. Managing Legitimacy: Strategic and Institutional Approaches. *Academy of Management Review*. **1995**, 20(3), 571-610.

(12) Epstein, E. M.; Votaw, D. Rationality, Legitimacy,, Responsibility: Search for New Directions in Business and Society, **1978**. Santa Monica, CA: Goodyear.

(13) Eden, S.E. Business, Trust and Environmental Information: Perceptions from Consumers and Retailers. *Business Strategy and the Environment.* **1994**, 3(4): 1-8.

(14) https://www.cas.org/content/chemical-substances/cas-registry-100-millionth-fun-facts

(15) http://support.cas.org/content/regulated-chemicals

(16) Lyon, T. P.; Mazwell, J. W. Greenwash: Corporate environmental disclosure under threat of audit. *Journal of Economics & Management Strategy*. **2011**, 20(1), 3-41.

(17) Markey CM, Wadia PR, Rubin BS, Sonnenschein C, Soto AM. Long-term effects of fetal exposure to low doses of the xenoestrogen bisphenol-A in the female mouse genital tract. *Biology of Reproduction*. **2005**, 72(6): 1344–51.

(18) Muñoz-de-Toro M, Markey CM, Wadia PR, Luque EH, Rubin BS, Sonnenschein C, Soto AM. Perinatal exposure to bisphenol-A alters peripubertal mammary gland development in mice. *Endocrinology*. **2005**, 146(9): 4138–47.

(19) Newbold RR, Jefferson WN, Padilla-Banks E. Prenatal exposure to bisphenol a at environmentally relevant doses adversely affects the murine female reproductive tract later in life. *Environmental Health Perspectives*. **2009**, 117(6): 879–85.

(20) Honma S, Suzuki A, Buchanan DL, Katsu Y, Watanabe H, Iguchi T. Low dose effect of in utero exposure to bisphenol A and diethylstilbestrol on female mouse reproduction. *Reproductive Toxicology*. **2002**, 16(2): 117–22.

(21) Layton, Lindsey (16 September 2008). “Study Links Chemical BPA to Health Problems”. *The Washington Post.* Pp. A03. Retrieved 18 May 2018.

(22) "General Mills to Pull BPA from Organic Tomato Cans, GreenerDesign.” Greenbiz.com. 19 April 2010. Retrieved 20 April 2018.

(23) Clayton, E. M., Todd, M., Dowd, J. B., & Aiello, A. E. The impact of bisphenol A and triclosan on immune parameters in the U.S. population, NHANES 2003-2006. *Environmental Health Perspectives.* **2010**, 119(3): 390-396.

(24) Allmyr, M., Adolfsson-Erici, M., McLachlan, M.S., & Sandborgh-Englund, G. Triclosan in plasma and milk from Swedish nursing mothers and their exposure via personal care products. *Science of the Total Environment.* **2006**, 372(1): 87-93.

(25) Stoker, T. E.; Gibson, E. K.; Zorrilla, L. M. Triclosan exposure modulates estrogen-dependent responses in the female wistar rat. *Toxicological Sciences*. **2010**, 117(1): 45-53.

(26) Yueh, M.; Tukey, R. H. Triclosan: A widespread environmental toxicant with many biological effects. *Annual Review of Pharmacology and Toxicology.* **2016**, 6: 251-272.

(27) Wang, C.; Chen, L.; Zhao, S.; Hu, Y.; Zhou, Y.; Gao, Y.; Wang, W.; Zhang, J.; Tian, Y. Impacts of prenatal triclosan exposure on fetal reproductive hormones and its potential mechanism. *Environment International.* **2017**, 111: 279-286.

(28) Kary, T. Triclosan: Four Decades of Regulatory Limbo. (August 11, 2014). Retrieved from https://www.bloomberg.com/graphics/infographics/triclosan-four-decades-of-regulatory-limbo.html

(29) Floyd, K.; Ramirez, A., Jr.; Burgoon, J.K. Expectancy violations theory. In L. K. Guerrero, J. A. DeVito, & M. L. Hecht (Eds.), *The nonverbal communication reader: Classical and contemporary readings* (2nd ed.): 437-444. **1999**. Prospect Heights, IL: Wakeland.

(30) Zucker, L.G. The Production of Trust: Institutional Sources of Economic Structure 1840-1920. *Research in Organizational Behaviour.* **1986**, 8: 53-111.

(31) Burgoon, M., Denning, V. P., & Roberts, L. Language expectancy theory. In J. P. Dillard & M. Pfau **(Eds.),** *The persuasion book: Developments in theory and practice:* **2002**, 117-136. Thousand Oaks, CA: Sage.

(32) Festinger, L. *A theory of cognitive dissonance.* **1957**. Stanford, GA: Stanford University Press.

(33) Greifeneder, R., Bless, H., & Pham, M. T. When do people rely on affective and cognitive feelings in judgment? A review. *Personality and Social Psychology Review.* **2011**, 15: 107-141.

(34) Zavyalova, A.; Pfarrer, M. D.; Reger, R. K.; Shapiro, D. A. Managing the Message: The Effects of Firm Actions and Industry Spillovers on Media Coverage Following Wrongdoing. *Academy of Management Journal.* **2012**, 55(5), 1079-1101.

(35) Chaiken, S., Liberman, A., & Eagley, A. H. Heuristic and systematic information processing within and beyond the persuasion context. In J. S. Uleman & J. A. Bargh (Eds.), *Unintended thought:* **1989**, 212-252. New York: Guilford.

(36) Slovic , P. Perceived Risk, Trust, and Democracy. *Risk Analysis*. **1993**, 13(6), 675-682.

(37) Nocella, G., Romano, D., Stefani, G. Consumers' attitudes, trust and willingness to pay for food information. *International Journal of Consumer Studies.* **2014**, 38, 153-165.

(38) https://www.mturk.com

(39) Freeman, J. The Political Culture of the Democratic and Republican Parties. *Political Science Quarterly*. **1986**. 101(3), 327-356.

(40) Barnett, M. L., Hoffman, A. J. Beyond corporate reputation: Managing reputational interdependence. *Corporate Reputation Review*. **2008**, 11, 1-9.

(41) Barnett, M. L., King, A. A. Good fences make good neighbors: A longitudinal analysis of an industry self-regulatory institution. *Academy of Management Journal*. **2008**, 51, 1150-1170.

(42) Kostova, T., Zaheer, S. Organizational legitimacy under conditions of complexity: The case of the multinational enterprise. *Academy of Management Review*. **1999**, 24, 64-81.

Appendices

Sample Demographics

GENDER	SAMPLE STATISTICS	US POPULATION STATISTICS
female	47%	51%
male	53%	49%
PARTY		
democrat	37%	31%
independent	37%	42%
republican	27%	24%
EDUCATION		
completed some high school	2%	8%
high school graduate (or equivalent)	18%	51%
associate's degree	13%	9%
bachelor's degree	49%	20%
graduate degree (masters, PhD or professional degree)	18%	13%
HOUSEHOLD INCOME		
less and $25,000	38%	21%
$25,000 - $40,000	38%	14%
$40,000 - $75,000	35%	26%
$75,000 - $150,000	22%	26%
more than $150,000	4%	12%
AGE		
18 - 24	16%	12%
25 - 34	47%	18%
35 - 44	21%	16%
45 - 54	8%	17%
55 - 64	5%	17%
65 and older	3%	20%

US population data from American Community Survey (https://www.census.gov/acs/www/data/data-tables-and-tools/index.php). US population data for household income are estimates, as household income bins do not align between ACS and our survey.

Survey Instrument:

Control Message:
Dssrttn Inc. produces and sells consumer products. They have a variety of suppliers who they source raw materials from, and Dssrttn acts as an intermediary to assemble and package the products before they go to market. They have products in several different markets, and they can be purchased both in-store and online. Most American households will purchase and use one or more of their products every year.

Here is an excerpt from a recent press release from Dssrttn:
"""…we at Dssrttn Inc. take chemical risk management very seriously. We are proud of our chemical risk management group and their continuous efforts to minimize the environmental and health risks from the use of our products. This past year, we dedicated even more resources to these efforts and brought to market more shower and bath products than ever before, offering consumers a wider range of options to meet their needs."

Treatment 1 [Control + Company Disclosure] Message:
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Treatment 2 [Media + Control + Company Disclosure] Message:
Last year the New York Times "Well" Blog, published an article titled "A Call for Action on Toxic Chemicals" (July 1, 2016). One of the chemicals that the article highlighted was phthalates: "These chemicals cross the placenta during pregnancy, and prenatal exposure has been linked in studies to problems with attention and intellectual deficits. The Consumer Product Safety Commission has banned the use of six phthalates in toys and child care

products, but they are still widely used in all kinds of products, from food packaging to personal care products and building materials."

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"…we at Dssrttn Inc. take chemical risk management very seriously. We are proud of our chemical risk management group and their continuous efforts to minimize the environmental and health risks from the use of our products. This past year, we lab-tested chemical ingredients from our suppliers, and decided to remove all phthalate ingredients from our shower and bath product lines, now making all of our products safer than ever before."

Treatment 3 [Media + Control] Message:
Last year the New York Times "Well" Blog, published an article titled "A Call for Action on Toxic Chemicals" (July 1, 2016). One of the chemicals that the article highlighted was phthalates: "These chemicals cross the placenta during pregnancy, and prenatal exposure has been linked in studies to problems with attention and intellectual deficits. The Consumer Product Safety Commission has banned the use of six phthalates in toys and child care products, but they are still widely used in all kinds of products, from food packaging to personal care products and building materials."

Dssrttn Inc. produces and sells consumer products. They have a variety of suppliers who they source raw materials from, and Dssrttn acts as an intermediary to assemble and package the products before they go to market. They have products in several different markets, and they can be purchased both in-store and online. Most American households will purchase and use one or more of their products every year.

Here is an excerpt from a recent press release from Dssrttn:
"…we at Dssrttn Inc. take chemical risk management very seriously. We are proud of our chemical risk management group and their continuous efforts to minimize the environmental and health risks from the use of our products. This past year, we dedicated even more resources to these efforts and brought to market more shower and bath products than ever before, offering consumers a wider range of options to meet their needs."

Survey Questions (all participant groups receive same questions about reading message):

How willing are you to purchase shampoo or bath products from this Dssrttn Inc.? (1-7 Likert scale)

How much do you trust Dssrttn Inc.? (1-7 Likert scale)

In addition to their bath and shower products, Dssrttn Inc. offers several other product lines. How willing are you to purchase another type of product from Dssrttn? (1-7 Likert scale)

Ettsuuo Inc. also sells bath and shower products. How willing are you to purchase shampoo or bath products from Ettsuuo? (1-7 Likert scale)

Do you think Ettsuuo Inc. uses phthalates in their products?

Now back to Dssrttn Inc… Do you think Dssrttn uses phthalates in their bath and shower products?

Do you think Dssrttn Inc. uses phthalates in their other products?

How risky do you think phthalates are in consumer products? (1-7 Likert scale)

What is your age?

Please select your political affiliation. (Democrat, Republic, Independent)

What is your gender? (male, female)

What is your annual income? (bins)

What is your highest education level? (completed some high school, high school graduate, completed some college, associate degree, bachelor’s degree, PhD, graduate or professional degree)

Chapter Three: *Toward employee-level adoption of sustainability in firms*

Introduction

Organizations are increasingly expected to align activities with those that are acceptable for members of society,[1,2] and with this comes pressure from various stakeholder groups to prioritize sustainability in their operations and business practices.[3,4] Firms today demonstrate a commitment to sustainability through the prevalence of ceremonial behaviors (e.g. voluntary sustainability reporting[7] and disclosure through information intermediaries[17,18]), allowing them to maintain social license to operate and be seen favorably by external stakeholders.[5,6] But decoupling can occur when firms develop formal programs in response to external pressures and do not follow through with actual integration at the employee-level.[8,9] This merely ceremonial adoption can be viewed as an implementation failure,[10] as was the case with total quality management (TQM),[10] job enrichment[11], quality circles[12], just-in-time (JIT) management[13], and reengineering, in which the rhetoric around each practice was stronger than the implementation itself. Given the strong external pressures for companies to adopt environmental stewardship and social responsibility programs,[14-16] sustainability initiatives could be at risk of implementation failure masked by ceremonial adoption to appease external stakeholders. How and where this implementation failure occurs is critical to understanding how sustainability managers can better integrate sustainability throughout their organizations and not just through ceremonial adoption.

An effective corporate sustainability agenda requires input from employees in all facets of the organization, as sustainability goals are typically holistic in nature. Targets focused on company-wide reductions in emissions, water use and waste generation, as well as product stewardship initiatives that claim responsibility across the entire product life-cycle,[7] cannot be carried out within one division of the company, but necessitate coordination of many small efforts to move the needle. Firms that tout sustainability missions and aspirations, but who do not effectively engage employees to take action, risk being criticized by external stakeholders for greenwashing[19] and are destined for the implementation failure characteristic of decoupling.[10] Companies seeking to develop successful sustainability programs need to take more than just a ceremonial approach and actually integrate sustainability practices throughout their organizations at the employee-level.

In rare instances, employees are incentivized to incorporate sustainability into their roles through performance reviews and compensation tied to specific sustainability objectives.[20] However, in most cases, sustainability initiatives rely on voluntary employee participation,[24] and sustainability leaders strive to understand the more and less effective tactics to increase the adoption of sustainability practices amongst employees in their organizations. Very few researchers have studied sustainability or CSR in organizations at the micro-level,[25,26] offering little guidance to sustainability managers looking to measure the baseline degree of integration and to identify effective communication practices to leverage. Just as measuring a company's external communications may not reflect well on their internal practices, measuring how employees talk about sustainability may not indicate how much they have adopted sustainability practices. While decoupling has been studied extensively at the organization level, this study assesses the degree of decoupling that can trickle down to the level of the individual, at which an employee may talk about certain initiatives without actually taking action to adopt new practices. Developing methods to measure both employee communication and action in this area will offer insights into the degree of decoupling occurring at the individual employee level and point to strategies to engage employees to communicate and/or take action related to sustainability.

Just like with other internal communications within large organizations, the sustainability team needs to use resources and time efficiently by matching communication routes and messaging frames with desired outcomes amongst different employee factions. The characteristics and perceptions of individual employees offer insights into which messaging can effectively facilitate employee adoption of sustainability practices. What motivates the internal rhetoric around an initiative may be very different than what motivates employees to take action; therefore, this work seeks to answer two separate questions: (1) What drives employees to talk about sustainability internally? (2) What drives employees to actually seek out sustainability knowledge? To answer these questions, an employee survey was conducted within a large consumer products company based in the United States. The following sections present the theoretical background, derived hypotheses, methodology and results, followed by a discussion of the findings and opportunities for future work.

Theoretical Background

A person's behaviors are largely influenced by their expectancies about that behavior, i.e. their beliefs about the expected outcomes associated with a given behavior influence their behavioral intentions.[49] In the context of sustainability, we expect an employee's perceptions about the outcomes associated with doing sustainability-related tasks to influence his or her willingness to adopt these practices. According to Ajzen and Fishbein's theory of reasoned action, an individual's behavioral intentions are a precursor to actual behavior change, and behavioral intentions are shaped by one's attitudes and subjective norms toward the behavior.[27,28] Broadly speaking, actions aligned with sustainability and other pro-social or pro-environmental behaviors carry a positive normative belief.[31] In organizations that publish external sustainability or CSR reports, this norm is reinforced amongst employees and can influence behavioral intentions. With a baseline positive norm associated with sustainability-related actions, individual employee attitudes may be strong determinants of behavioral intentions. People's attitudes toward a behavior can be determined by their subjective belief that the behavior will generate a certain outcome.[34] Three different attitudes toward sustainability will be evaluated in this study as drivers: perceived cost savings from sustainability-related actions, perceived market value of sustainability in consumer product offerings, and personal motivations around sustainability. The rationale for studying each of these drivers will be discussed later in this section, but first we consider how these drivers may be more or less effective depending on an individual's confidence in the desired outcome associated with different sustainability-related behaviors.

Ajzen's more recent theory of planned behavior builds off of the theory of reasoned action, introducing perceived behavioral control as a third factor influencing behavioral intentions and behavior.[29] In the theory of planned behavior, perceived behavioral control helps to explain why individuals have behavioral intentions that do not turn into actual behaviors. The concept of perceived behavioral control is closely related to the concept of self-efficacy in that it is a measure of one's perceived ease or difficulty in performing the actual behavior.[30] An individual with behavioral intentions is more likely to actually change their behavior if they think they can do so successfully. Perceived behavioral control may be different for different kinds of sustainability-related actions. Some actions related to sustainability may be very straightforward and simple, with employee perception of behavioral control being high, while others may seem overwhelming or infeasible, resulting in a low behavioral control. Research in environmental psychology has pointed to low perceived behavioral control as the reason why some individuals have intentions to engage in pro-environmental behavior but do not necessarily turn those intentions into actions because the problems seem too overwhelming to find solutions.[46] This influence of perceived behavioral control, in combination with employee attitudes toward sustainability, will be relevant in understanding to what degree employees communicate and/or take actions related to sustainability within an organization.

Since little research has been developed on the employee-level drivers of sustainability within firms, this work considers the more extensive research on the firm-level and macro-scale drivers of corporate sustainability[4,32] as a starting point. At this broader scale, the relevant norms to drive behavior are related to external pressures and societal norms that firms follow to ensure social license to operate.[7,8] At the individual employee level, behavioral intentions may be driven by company-wide norms and the degree to which the sustainability agenda has been formally institutionalized.[33] Just as sustainability actions carry a positive normative belief theoretically, preliminary research pointed to the same notion at the employee level in our study. While the degree to which sustainability-related actions are viewed positively may vary from group to group, the existence of formal internal programs and external communications about the value of sustainability offer evidence that there is a positive norm associated with sustainability-related actions by individual employees at this company. Employee interviews reinforced this concept with many examples of interviewees proudly describing the sustainability contributions of individuals or groups of employees in their organization.

This work is focused on understanding the drivers of sustainability-related employee behaviors. We will next introduce three different employee attitudes that we expect to be associated with employee engagement in sustainability, then we will present hypotheses as to whether each of these attitudes will be associated with two different behaviors, internal sustainability communication and sustainability information seeking. Some employee attitudes toward a behavior are likely to reflect their perception of how that behavior influences the organization. A priority that is consistent across all for-profit organizations is the bottom-line, and research has demonstrated that at the firm-level sustainability initiatives can be driven by bottom-line incentives from two different angles: cost reductions and increased market value.[35] In addition to the perceptions that sustainability can improve the organization's bottom line, employee attitudes can also be shaped by their personal values and interests. An individual's motivation to incorporate sustainability into their personal decisions are likely to spill over into their behaviors at work. Drawing on existing literature and anecdotal evidence from preliminary on-site interviews, here we explore the potential of each of these attitudes toward sustainability – perceived cost reductions, perceived market value, and personal motivation – to influence employee behavior.

Perceived Cost Reductions

Many organizations report cost savings realized through sustainability initiatives such as energy use reductions, minimized waste disposal and treatment, and reduced raw materials requirements;[36] however, the perception that sustainability can make projects more expensive (i.e. renewable energy technologies like solar that still require subsidies to be price competitive[37]) also exists. During one interview an employee highlighted the value of sustainability from a waste reduction perspective: "…it's a cost to throw things in the garbage", and several others alluded to efficiencies gained through sustainability. Alternatively, a different employee described the challenges of using more sustainable input materials: "Most of the 'sustainable options' are higher cost, variable performance, and riskier, so it only really fits if it dovetails into one of the products." Employees who perceive sustainability actions to have utility as a means to reduce costs throughout the organization will likely have stronger behavioral intentions around sustainability actions.

Perceived Market Value

Similar to cost reductions, customer demand and increased market share are largely interpreted as drivers of sustainability at the organization level.[38-41] Interviews of company employees revealed sentiments that customers were interested in having sustainable or "green" products; however, there was significant variability in the degree to which employees believed customers cared about this feature. Employees believed customer segments within some product lines had more interest than others, and some employees expressed opinions that the market did not care about sustainability yet, but that it was expected to in the future. In reflecting on the company's sustainability program, one employee stated: "I think we've done a good job externally, customer-focused… there's a business drive to produce safe and sustainable products, so we invest in it." Another employ expressed that "There's also a lot of misinformation about what customers want and what customers know in the sustainability arena." And a third employee took another stance on sustainability in the market: "It is important to our customers, with an asterisk, since its more our future customers, and today it doesn't really drive the customers…it's more of a question of when it will be become more important, not if." For individual employees, the degree to which they hold perceptions about the benefits of sustainability in the market will likely influence behavioral intentions.

Personal Motivations

In addition to the perception that sustainability behaviors lead to improvements for the organization's bottom line, employee attitudes can also be shaped by their personal values and interests. According to self-determination theory, the type of motivation of a given individual is an important determinant of behavior.[42-44] Graves and colleagues demonstrated that autonomous motivation – i.e., pursuing an activity because it matches one's values and goals – was correlated with employee commitment to environmental sustainability and pro-environmental behaviors.[45] In addition, voluntary workplace green behaviors have been linked to personality characteristics, including moral reflectivity and conscientiousness,[46] suggesting that people who care more about sustainability are more likely to include it in their work. One employee touched on their opinion of how sustainability should be implemented within the organization: "I don't believe legislating is the answer, it needs to be written in your heart…for some people this is the case, for others not so much." Several others pointed to personal motivations as a primary driver for why some employees were more knowledgeable than others on the topic of sustainability.

Determinants of Sustainability-Related Behaviors

Along with the associated positive norm, all three of these attitudes towards sustainability actions (perceived cost reductions, perceived market value, and personal motivation) influence an individual's behavioral intention and actual behavior related to sustainability. The remaining factor shaping intentions and behaviors is the perceived behavioral control associated with that action. In this study the two employee behaviors of interest are internal communication about sustainability and sustainability information-seeking behavior. For organizations seeking to fully integrate sustainability programs talking about sustainability is a great starting point, as it can be an indicator of employee awareness of sustainability initiatives within the company. Measuring the extent of an employee's communications with others about sustainability will capture the degree to which it has been formally adopted by the individual. Since decoupling can occur at the individual level, we want to further investigate whether actions beyond communication are being taken by employees. By also measuring sustainability information seeking behavior this study seeks to determine what moves employees from simply talking about it to actually changing behavior.

Sustainability Communication

The perceived behavioral control associated with sustainability communication with other employees in the organization is expected to be high. Individuals will communicate about topics that they believe to be relevant to others within their knowledge community;[21,22] therefore, if an individual believes there is value to the organization then they will expect peers and other employees to share the same notion and will be more likely to discuss the topic with others. There are no major obstacles preventing one employee from sharing information with another, especially given the positive norm associated with sustainability throughout the organization. Spreading the word about sustainability to other employees is an attainable goal with little risk involved. For this reason, all three attitudes towards sustainability are expected to shape not just behavioral intentions but also behaviors to communicate about sustainability topics with other employees. This leads to the following hypotheses:

H1: Employees who perceive sustainability to generate cost reductions for the organization will have greater internal sustainability communication.

H2: Employees who perceive sustainability to generate market value for the organization will have greater internal sustainability communication.

H3: Employees who have a higher personal motivation for sustainability will have greater internal sustainability communication.

Sustainability Information Seeking

Talking about sustainability is much easier than actively seeking out information to learn more. In a study of information seeking behavior amongst engineers within a firm, Robinson found that seeking out information from human sources required much less effort on the part of the individual than seeking information from a non-human source.[47] In communications between employees, Robinson demonstrated that individuals will spend more time receiving information that they have not requested than they will receiving information that they have. The fraction of useful information that one can obtain from a source is often correlated with the amount of effort he or she dedicates up front to identify a more specific source aligned with the information need.[48] As a precursor to the larger effort required to find a specific source to meet an information need, an individual must know what they are looking for. The definition of sustainability within an organization is often unclear, with many different external explanations and varying scopes from one company to another.[48] One employee lamented that the definition of sustainability "has changed hugely within the last ten years, especially in [her] part of the organization, and there's an opportunity for more clarity." When asked to describe how sustainability fits into the mission and strategy of their organization, several other interviewees reported that the question was difficult to answer or gave long-winded responses listing many different anecdotal examples. The potential confusion around objectives and outcomes of sustainability initiatives can decrease an individual's perceived behavioral control due to the uncertainty around how to achieve unclear objectives. Employees' perceived behavioral control for information seeking is expected to be generally much lower than for communicating about anything sustainability-related internally.

Revisiting the three attitudes toward sustainability that may shape employees' behavioral intentions and actual behaviors, we consider the strength of each relative to the lower perceived behavioral control associated with sustainability information seeking. Each attitude toward sustainability will have an associated outcome that a behavior is thought to achieve. The nature and likelihood of each outcome may play a role in which attitudes are the stronger drivers of sustainability information seeking. Attitudes defined as personal motivations towards sustainability are simpler to analyze within the model of planned behavior: perceived behavioral control may be low, but if personal motivation is strong enough then sustainability information seeking will occur. To achieve the outcome associated with this attitude, which is to achieve sustainability itself, low self-efficacy needs to be overcome. On the other hand, attitudes towards sustainability that are created by perceived cost reductions and perceived market value associated with the behaviors may have a less direct link to behavior change. The outcome in both of these instances is increased value for the organization, and in light of a low perceived behavioral control to achieve that through sustainability behaviors, employees may look to other behaviors that achieve the same outcome. As opposed to attitudes driven by personal interests in sustainability, the perceived behavioral control seems lower relative to the alternative paths to achieving the desired outcome that have nothing to do with sustainability (e.g. another type of product feature that does not qualify as sustainable but that increases the market value with fewer risks or uncertainties). For this reason, only the personal motivation attitude is expected to influence information seeking behavior:

H4: Employees who have a higher personal motivation for sustainability will have greater sustainability information seeking behavior.

As mentioned earlier, confusion around the meaning of sustainability can contribute to the low perceived behavioral control associated with sustainability actions; therefore, we expect that for employees to engage in this information seeking behavior they will need a threshold amount of understanding of sustainability. A better understanding will allow them to specify their information needs to identify useful content, empowering employees to act upon sustainability-related behavioral intentions. This effect may flow in the opposite direction as well, since the more an individual seeks out sustainability information, the better their understanding of the concept and practices should be. This leads to the fifth, and final, hypothesis:

H5: Employees with a greater understanding of sustainability have greater sustainability information seeking behavior.

These hypotheses were tested through employee surveying within a large organizational setting. A description of the organization and data collection methodology is described in the following section.

Methods

Study Design

Our study was conducted within a large consumer products manufacturing organization based in the United States. The organization employs over 10,000 people, ranging from scientists and researchers, to marketing and sales professionals. The company had recently gone through a reorganization and the newly formed sustainability team was interested in understanding the optimal strategies for sharing sustainability-related knowledge throughout the organization to incite broader participation in company-wide sustainability initiatives. Twelve on-site interviews were completed in November 2017 at the company's headquarters to validate the theoretical hypotheses and inform the full survey design. The interviewees were seen as sustainability proponents within their own facets of the organization, representing marketing, purchasing, sales, and R&D within different business units. The length of the interviews ranged from twenty minutes to one hour, covering a range of questions related to how sustainability information was transferred throughout the organization, what they observed about employees who were more or less engaged in sustainability, and how sustainability was defined within the organization. The interview protocol is included in *Appendix A*.

The full survey was administered in March 2018 to roughly 6,500 employees within the organization. The target participants were primarily from the marketing, R&D, sales, and purchasing job families; however, employees from corporate functions such as human resources and customer service were included as well. The voluntary and anonymous survey was administered internally and was live for eight days (six business days), with a reminder sent out at the beginning of the fifth day. Demographic information (job division, job level, tenure, age, and job family) were auto-populated into the survey, which was expected to take 5-10 minutes total. Actual survey completion times were difficult to measure since many employees left the survey open and did not complete it all in one sitting. A mock-up of the entire survey is included in *Appendix B*.

Measures

In addition to demographic factors, the survey was used to measure four independent variables that are hypothesized to be attitudes driving sustainability-related behaviors. *Perceived cost reduction* is operationally defined as the degree to which the employee reportedly thought sustainability influenced costs within the organization. *Perceived customer value* is operationally defined as the degree to which the employee reportedly thought customers cared about sustainability attributes in their products. *Personal motivation* is operationally defined as the degree to which the employee reportedly cared about sustainability. Data for all three of these variables was collected through survey questions with six answer options (five-point Likert scale and "I don't know"). Since these three variables were intended to distinguish employees with a true opinion about something sustainability-related from those who were indifferent or lacking knowledge, the Likert scales for each of these variables (*perceived cost reductions*, *perceived customer value*, and *personal motivation*) were collapsed to simplify the data analysis.

Table 1. Operationalization of Independent Variables

Independent Variable	*Collapsed Likert Scale Values*	*Corresponding Survey Responses*
Perceived Cost Reductions	Perceived Cost Increases	"greatly increases costs" "slightly increases costs"
	Perceived Cost Neutral	"does not influence cost" "I don't know"
	Perceived Cost Decreases	"slightly reduces costs" "greatly reduces costs"
Perceived Market Value	Low Perceived Customer Value	"they do not care at all" "they do not care much" "they are indifferent" "I don't know"
	High Perceived Customer Value	"they care somewhat" "they care very much"
Personal Motivation	Low Personal Motivation	"it is not important to me at all" "it is not very important to me" "I am neutral about it" "I don't know"
	High Personal Motivation	"It is somewhat important to me" "it is very important to me"

The resulting operationalization of the variables is presented in Table 1. Collapsing Likert scales in data analysis can be appropriate when observations are skewed and there are very few observations within one category.[23] This was determined to be the case for the dataset, since out of 886 respondents there were only seven participants who selected "They do not care at all" for *perceived customer value* and only four who selected "It is not important to me at all" for *personal motivation*, both the lowest ranking option on their respective scales. Responses from the original Likert scale for perceived customer value and personal motivation were binned into two groups, low and high. Because sustainability could be observed to increase or decrease costs, the results for perceived cost reductions were binned into three groups based on the absolute perceptions: increases, neutral and decreases.

Lastly, *understanding* is operationally defined as how clear the employee reportedly believed the meaning of sustainability to be within the organization (four-point Likert scale from "not clear at all" to "very clear").

Two dependent variables were constructed based on the survey questions. A measure of employee *sustainability communication* was used to evaluate the first three hypotheses. Before measuring communications specifically about sustainability, questions about general communication were included. The resulting communication metric (described below) will be compared to that just for sustainability communications to determine whether different patterns were observed in sustainability communications than in other communication throughout the organization. The survey respondents were asked to answer two multi-part questions about their general communication habits: (1) how many employees they communicate with in each department and (2) on average how frequently these communications occurred with individuals in each department. To generate a communication intensity metric for each employee, the value that they reported for how many people they communicated with, P, in each department, i, was multiplied by their reported average frequency, F, of communication with people in that department. This provided a score for an employee's communication intensity with each individual department, $P_i * F_i$, and by summing across all departments an ultimate internal communication intensity, C, for each individual employee could be generated:

$$\mathrm{C} = \sum_i^k P_i * F_i$$

Respondents were asked the same questions a second time, but specifically in the context of communicating about sustainability topics. The same method was applied to the questions specifically about sustainability communications, such that a sustainability communication intensity score, sC, could be calculated for each individual respondent as well:

$$\mathrm{sC} = \sum_i^k sP_i * sF_i$$

Therefore, the *sustainability communication* dependent variable, sC, is operationally defined as the frequency and intensity at which an employee reportedly talks about sustainability within the organization, and it is used as the outcome variable to test the first three hypotheses.

The second dependent variable was a measure of *sustainability information seeking* that drew upon five different questions within the survey. One question asked each respondent if he/she sought out information about sustainability from sources outside the organization, and from a list of options they were asked to select all of those source types that they searched within (if any). Respondents were given one point if they answered that they sought out any sustainability information externally, regardless of how many source types they reported using. There were four open ended questions at the end of the survey in which they could request more or specific information from the sustainability group by: (1) indicating which sustainability topics they wanted more information on, (2) describing the kind of information they needed or wanted to be able to address sustainability-related issues in their role, (3) providing alternative ways in which they'd like to receive future communications, and (4) offering any other thoughts or suggestions for the company's sustainability group. They were given one additional point for each of these four open-ended questions that they answered with a meaningful answer (i.e. not "I don't know" or a similar response). Employees could therefore obtain a score of 0 – 5 for this outcome variable, depending on how actively they were seeking out information both retrospectively and within the survey itself. This second outcome variable, *sustainability information seeking*, measured employee behavior to actively seek out sustainability-related information and was used to test our latter two hypotheses.

Results

Of the total survey recipients, 14% (886 total) completed the survey (partial responses were excluded from the analysis). The demographics of the survey population are included in Table 2, and are believed to be consistent with the company's demographics based on review by the company's sustainability team (disclosure of company-wide demographics was not permitted in this study).

Table 2. Sample Demographics

Job Family	
Sales	334
R&D	310
Marketing	105
HR	51
Customer Service	49
Purchasing	37
Job Level	
Individual Contributor	556
Manager of Others	245
Manager of Managers	85
Tenure	
<1yr	42
1-4yrs	189
5-9yrs	148
10-14yrs	134
15-19yrs	122
>20yrs	251
Age	
<24	17
25-34	173
35-44	202
45-54	283
>55	211

Given how little is known about internal patterns of employee communication around sustainability topics, the relationship between how employees communicate in general versus specifically about sustainability was explored. Not surprisingly, the findings indicate a positive correlation between behavior to communicate in general and to communicate about sustainability. Figure 1 displays the positive correlation (0.462, p<0.001) between C and sC for all employee respondents in the survey

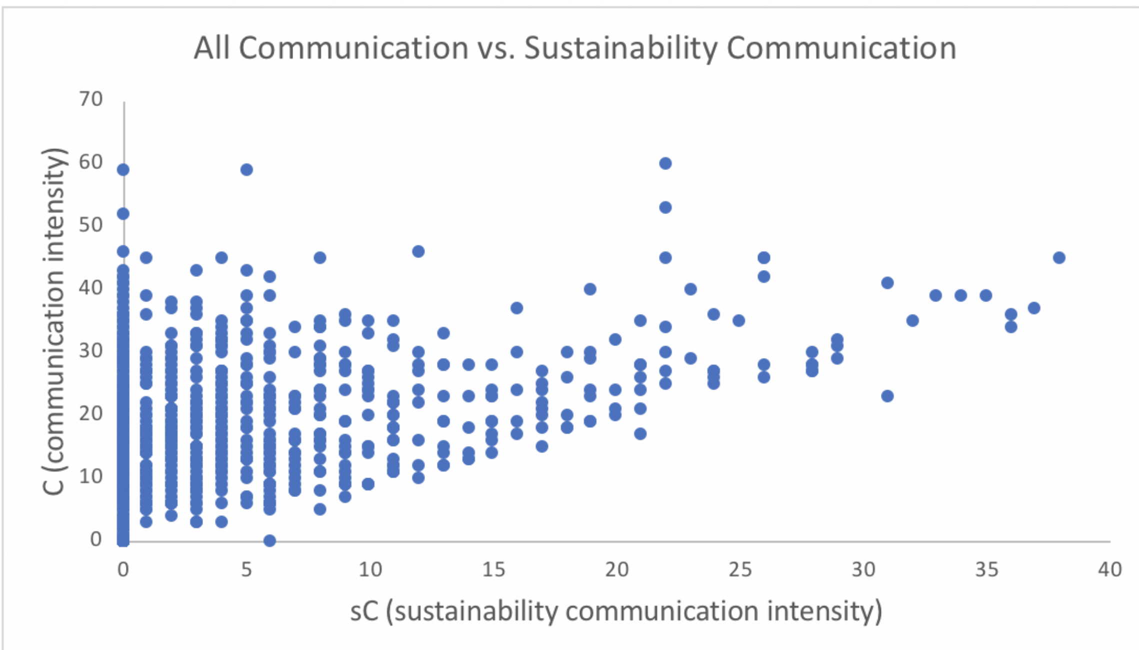

Figure 1. Relationship between general communication (C) and sustainability-specific communication (sC) for individual employees (R-squared = 0.109)

Focusing on just communication that is external from one's own department, inter-department communication trends were analyzed to determine whether they differ significantly from what is observed around sustainability communication. Figure 2 presents comparative network diagrams for the inter-department communications in these two scenarios. The tie strength (line weight) represents the average communication intensity reported across all employees from one department to another given department relative to the rest of the data within that diagram's dataset. This display qualitatively demonstrates the alignment of sustainability communications with typical inter-departmental communication patterns.

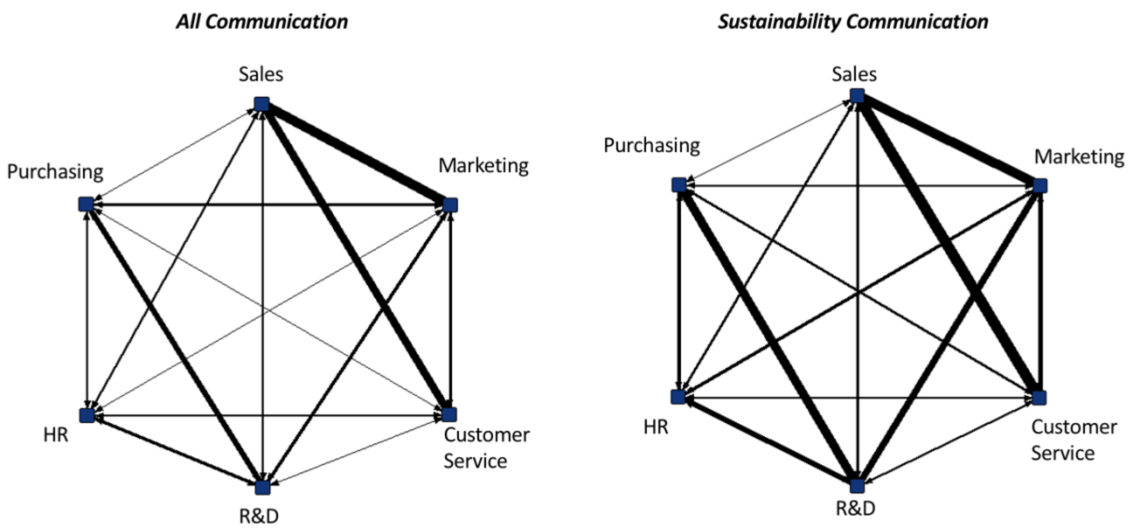

Figure 2. Network diagram of one-way communication patterns between departments, both for all communication (left) and specifically for sustainability

To compare the differences between what drives people to talk about sustainability versus actual take action within an organization, the relationships between the three different attitudes and the two outcome variables, *sustainability communication* and *sustainability information seeking*, were measured, as well as the influence of *understanding* on both dependent variables. Table 3 displays results for the multiple regression analysis using both ordered factor variables (*perceived customer value, perceived cost reductions, personal motivation, age, tenure,* and *job level*) and unordered factor variables (*job family*). Model 1 for each outcome variable only includes demographic factors as independent variables, while

Model 2 for each scenario includes the four independent variables represented in the hypotheses.

Table 3. Model Results for Outcome Variables. Model 1 includes just demographic independent variables and Model 2 also includes drivers evaluated within study hypotheses.

	Sustainability Communication		Sustainability Information Seeking	
	Model 1	*Model 2*	*Model 1*	*Model 2*
Perceived Customer Value		1.246**		0.327
Perceived Cost Reductions		1.482***		0.034
Perceived Cost Reductions^2		0.841		0.259*
Personal Motivation		0.135		0.607***
Understanding		1.222		0.084
Understanding^2		-0.172		0.094
Understanding^3		0.375		0.102
Age	2.319	2.515*	-0.269	-0.264
Age^2	0.144	0.082	0.550*	0.524*
Age^3	0.497	0.498	-0.399*	-0.403*
Age^4	-0.449	-0.388	-0.017	-0.001
Tenure	0.492	1.117	-0.442*	-0.223
Tenure^2	-1.118	-1.326	0.004	-0.052
Tenure^3	-1.112	-0.867	-0.214	-0.140
Tenure^4	0.225	0.142	-0.100	-0.122
Tenure^5	0.289	0.286	0.164	0.172
Job Level	1.914**	1.775**	0.195	0.095
Job Level^2	-0.479	-0.459	0.074	0.089
Job Family: Customer Service (reference)	-	-	-	-
Job Family: HR	-2.123	-2.635	0.605	0.522
Job Family: Marketing	0.099	-0.036	0.580*	0.513
Job Family: Purchasing	0.653	0.287	0.574	0.366
Job Family: R&D	0.337	0.016	0.798**	0.679**
Job Family: Sales	0.300	0.012	0.593*	0.464
Constant (intercept)	5.045***	5.039***	3.964***	3.768***
Multiple R-squared	0.052	0.106	0.036	0.108
F-statistic	2.992 on 16 and 869 DF	4.436 on 23 and 862 DF	2.051 on 16 and 869 DF	4.528 on 23 and 862 DF
p-value	6.86E-05	3.65E-11	8.68E-03	1.72E-11

Sustainability communication (sC) is the outcome variable used to measure the extent to which an employee talks about sustainability with other employees internally. To test the first three hypotheses, the relationship was analyzed between this variable and different employee attitudes toward sustainability actions: *perceived cost reductions* (*H1*), *perceived market value* (*H2*), and *personal motivation* (*H3*). Controlling for demographic factors, our results indicate that perceived cost savings and perceived market value both have a significant positive relationship with the intensity of sustainability communication by individual employees (1.482, $p<0.001$ and 1.246, $p=0.001$ respectively). These results support the first and second hypotheses, demonstrating that perceived bottom-line values of sustainability to the organization are common amongst employees who talk more about sustainability internally. Personal interest was not a significant predictor of sustainability communication in the model; therefore, the third hypothesis is unsupported. Age and job level were also significant predictors, as more internal sustainability communication was observed amongst employees who were older (2.515, $p=0.040$) and in more senior job levels (1.775, $p=0.003$). The lack of support for personal interest as a predictor of sustainability communication may be explained by the more intimate nature of this attitude toward sustainability. The other two attitudes (perceived cost reductions and perceived market values) are outcomes relevant for the whole organization, and thus are more likely to be common topics relevant in conversation with other employees. Personal interests are just that, personal, and may not be based on shared experiences or outcomes that provide the basis for conversation.

For the second outcome variable, *sustainability information seeking*, 45% of employees had scores of 0, indicating that they did not report seeking out any sustainability information externally or respond to any of the open-ended questions at the end of the survey. The information scores of 1 – 5 were distributed across the rest of the participants as follows: 21%, 8%, 10%, 10%, and 6% from 1 to 5, respectively. The fourth and fifth hypotheses consider what drives this behavior to seek out information about sustainability. Results of the regression analysis demonstrate a significant positive correlation between personal motivation and information seeking behavior in the context of sustainability (0.607, $p<0.001$); thus *H4* is supported. The relationship between employee understanding of sustainability and information seeking behavior is slightly positive but insignificant (0.084, $p=0.564$); therefore, the final hypothesis is not supported. Demographic factors, including age, tenure and job level, also were not predictors of sustainability information seeking; however, job family may be relevant, as employees in the R&D function were more likely to seek out sustainability information (0.679, $p=0.005$).

To further examine this relationship between personal motivation for sustainability and information seeking behavior, the second outcome variable can be dissected. The initial results demonstrate a correlation between personal motivation and information seeking behavior, but without directionality it may be possible that employees who seek out sustainability information (for unexplored reasons) then become more personally interested. By removing the question about prior seeking of external sustainability information, it is possible to evaluate whether the analysis of an outcome variable based only on requests for future information (after personal motivations have already been reported) is consistent with the initial results. Personal motivations had a similar positive relationship with future information requests (0.836, $p<0.001$), as was observed with all information seeking behavior. In addition, employees in the R&D function were more likely to request future information about sustainability (0.898, p=0.015), as was the case in analysis of the more holistic outcome variable.

If personal motivation is the differentiator that leads to employee engagement and action around sustainability in the workplace, then understanding the determinants of these personal motivations can offer insights into how management practices can facilitate this behavior. In a subgroup analysis, employees in the high personal motivation group were compared to those in the low personal motivation group (as distinguished in Table 1). The two factors that distinguished employees with personal motivations towards sustainability from those without were the degree of understanding of the meaning of sustainability and tenure. Of the employees in the personally unmotivated category, the largest faction (48%) reported that the meaning of sustainability within the organization was “not clear at all” (0 on 0 – 3 Likert scale). This starkly contrasted the response from the personally motivated group, which had the largest portion of respondents (41%) select that the meaning of sustainability was “somewhat clear” (2 on 0 – 3 Likert scale) to them. Efforts to define and clarify the definition of sustainability, particularly within the context of the organization could be one step to increase employee engagement in sustainability initiatives. A small negative effect of tenure on personal interest in sustainability (-0.141, p=0.003) also suggests that employee turnover may help to increase employee engagement in sustainability across the organization.

Discussion

This study measured the differences in drivers that influence employees to talk about sustainability within their organization versus actually take action to engage more in sustainability topics by seeking out more information. Depending on the objectives of an organization, either outcome could be of interest. Ceremonial adoption of sustainability to increase public perception and maintain legitimacy in the eyes of shareholders could be a company's strategy. For this kind of company, employees could be encouraged to talk about sustainability in the context of the firm's formal policies without disrupting their work practices or priorities. This study determined that this kind of behavior is driven by an employee belief that sustainability adds value to the organization through cost reductions and increased customer value; therefore, rhetoric around these topics can facilitate formal institutionalization of sustainability from the organization down to the employee level.

But what if the organization's goal is for employees to more than just talk about sustainability? The study results indicate that the motivations that get employees talking about sustainability do not necessarily incite them to act on these topics. Personal motivations were determined to be the primary driver of employee actions around sustainability, observed through information seeking behavior. The employees within the organization with strong personal interests in sustainability also had a better understanding of the meaning of sustainability at the company, suggesting that clearer definitions in communications may be effective at increasing employee adoption of sustainability-related practices. For organizations that are trying to reach holistic sustainability targets, it is important that these actions are the focus of evaluation rather than just the rhetoric around the issues. This study sheds light on the importance of selecting the correct indicator when measuring employee behavior, as employee rhetoric may not reflect actual employee practices. Sustainability provides a good example to highlight this point; however, this methodology could be expanded to assess employee-level decoupling of formal and technical practices in other areas of a firm, such as financial reporting or supply chain management.

This study expands the knowledge of the micro-scale drivers of sustainability within organizations, measuring the differences between the determinants of formal and technical adoption. Given the nature of the study, all data was self-reported by employees, and future work should include experimental designs that test these findings in empirical settings. This case study focused on a well-established consumer goods manufacturing company based in the United States, and findings may be very different for a company farther upstream in the supply chain, at an earlier stage of company growth, or in a different geography. Future work should test the generalizability of these findings by comparing across different company types.

References

(1) Brunsson, N. *The organization of hypocrisy: Talk, decisions and actions in organizations.* **1989**. Chichester, UK: John Wiley and Sons.

(2) Bromley, P. & Powell, W.W. From Smoke to Mirrors to Walking the Talk: Decoupling in the Contemporary World. *The Academy of Management Annals*, **2012**, DOI:10.1080/19416520.2012.684462

(3) Thorlakson, T., de Zegher, J.F. & Lambin, E.F. Companies' contribution to sustainability through global supply chains. *PNAS*, **2018**, online: https://doi.org/10.1073/pnas.1716695115

(4) Serafeim, G. The Fastest-Growing Cause for Shareholders Is Sustainability. *Harvard Business Review*, **2016**, online: https://hbr.org/2016/07/the-fastest-growing-cause-for-shareholders-is-sustainability

(5) Suchman, M. C. Managing Legitimacy: Strategic and Institutional Approaches. *Academy of Management Review*. **1995**, 20(3), 571-610.

(6) Epstein, E. M.; Votaw, D. Rationality, Legitimacy,, Responsibility: Search for New Directions in Business and Society, **1978**. Santa Monica, CA: Goodyear.

(7) https://3blmedia.com/News/Flash-Report-82-SP-500-Companies-Published-Corporate-Sustainability-Reports-2016

(8) Scott, W. R. *Institutions and organizations: Ideas and interests* (3rd ed.). **2008**. Thousand Oaks, CA: Sage Publications, Inc.

(9) Meyer, J. W., & Rowan, B. Institutionalized organization: Formal structure as myth and ceremony. *American Journal of Sociology*, **1977**, 83(2): 340-363.

(10) Zbaracki, M. J. The Rhetoric and Reality of Total Quality Management. *Administrative Science Quarterly*, **1998**, 43: 602-636.

(11) Hackman, J. R. Is job enrichment just a fad? *Harvard Business Review*, **1975**, 53(5): 129-138.

(12) Lawler, E. E., III, & Mohrman, S. A. Quality circles after the fad. *Harvard Business Review*, **1985**, 63(1): 65-71.

(13) Zipkin, P. H. Does manufacturing need a JIT revolution? *Harvard Business Review, January-February*, **1991**, 40-50.

(14) Yalabik, B., & Fairchild, R. J. Customer, regulatory, and competitive pressure as drivers of environmental innovation. *International Journal of Production Economics,* **2011**, 131: 519-527.

(15) Guoyou, Q., Saixing, Z., Chiming, T., Haitao, Y., & Hailiang, Z. Stakeholders' influences on corporate green innovation strategy: A case study of manufacturing firms in China. *Corporate Social Responsibility and Environmental Management,* **2013**, 20(1): 1-14.

(16) Triguero, A., Moreno-Mondéjar, L., & Davia, M. A. Drivers of different types of Eco-innovation in European SMEs. *Ecological Economics,* **2013**, 92: 25-33.

(17) Kolk, A., Levy, D., & Pinkse, J. Corporate Responses in an Emerging Climate Regime: The Institutionalization and Commensuration of Carbon Disclosure. *European Accounting Review*, **2008**, 17(4), 719-745.

(18) Depoers, F., Jeanjean, T., & Jérôme, T. Voluntary Disclosure of Greenhouse Gas Emissions: Contrasting the Carbon Disclosure Project and Corporate Reports. *Journal of Business Ethics,* **2016**, 134: 445-461.

(19) Lyon, T.P. & Montgomery, A.W. The Means and End of Greenwash. *Organization & Environment*, **2015,** 28(2): 223-249.

(20) Lubber, M.S. Compensation and Sustainability. *Harvard Business Review*, **2010.** Accessed online at https://hbr.org/2010/04/compensation-and-sustainabilit

(21) Bechky, B. Sharing meaning across occupational communities: The transformation of understanding on the production floor. *Organization Science*, **2003,** 17: 99-120.

(22) Brown, J.S. & Duguid, P. Knowledge and organization: A social-practice perspective. *Organization Science*, **2001,** 12(2): 198-213.

(23) Jacoby, J. & Matell, M.S. Three-Point Likert Scales Are Good Enough. *Journal of Marketing Research*, **1971,** 8(4): 495-500.

(24) Kim, A., Kim, Y., Han, K., Jackson, S. E., & Ployhart, R. E. Multilevel Influences on Voluntary Workplace Green Behavior: Individual Differences, Leader Behavior, and Coworker Advocacy. *Journal of Management,* **2014**, 43(5): 1335-1358.

(25) Aguinis, H., & Glavas, A. What we know and don't know about corporate social responsibility: A review and research agenda. *Journal of Management,* **2012**, 38: 932-968.

(26) Andersson, L. M., Jackson, S. E., & Russell, S. V. Greening organizational behavior: An introduction to the special issue. *Journal of Organizational Behavior,* **2013**, 34: 151-155.

(27) Fishbein, M. & Ajzen, I. Belief, attitude, intention, and behavior. **1975**. Reading, MA: Addison-Wesley.

(28) Ajzen, I. & Fishbein, M. Understanding attitudes and predicting social behavior. **1980**. Englewood Cliffs, NJ: Prentice Hall.

(29) Ajzen, I. The theory of planned behavior. *Organizational Behavior and Human Decision Processes,* **1991**, 50(2): 179-211.

(30) Bandura, A. Self-efficacy mechanisms in human agency. *American Psychologists.* **1982**, 37: 122-147.

(31) Sawitri, D.R., Hadiyanto, H. & Hadi, S.P. Pro-Environmental Behavior from a Social Cognitive Theory Perspective. *Procedia Environmental Sciences,* **2015**, 23: 27-33.

(32) Díaz-García, C., González-Moreno, A., & Sáez-Martínez, F. J. Eco-innovation: insights from a literature review. *Innovation,* **2015**, 17(1): 6-23.

(33) Powell, W. W., & DiMaggio, P. J. *The New Institutionalism in Organizational Analysis*. **1991**. Chicago: University of Chicago Press.

(34) Ajzen, I. & Fishbein, M. A Bayesian analysis of attribution process. *Psychological Bulletin*, **1975**, 82(2): 261-277.

(35) Díaz-García, C., González-Moreno, A., & Sáez-Martínez, F. J. Eco-innovation: insights from a literature review. *Innovation.* **2015**, 17(1): 6-23.

(36) Pereira, A., & Vence, X. Key business factors for Eco-innovation: An overview of recent firm-level empirical studies. *Cuadernos de Gestion.* **2012**, 12: 73-103.

(37) Institute for Energy Research (IER). The High Cost of Rooftop Solar Subsidies. **2016**. Prepared by: Arduin, Laffer & Moore Econometrics. Accessed on May 24, 2016. http://instituteforenergyresearch.org/wp-content/uploads/2016/10/The-High-Cost-of-Rooftop-Solar-Subsidies-Oct-16.pdf

(38) Doran, J., & Ryan, G. Regulation and firm perception, Eco-innovation and firm performance. *European Journal of Innovation Management.* **2012**, 15: 421-441.

(39) Grunwald, A. On the roles of individuals as social drivers for Eco-innovation. *Journal of Industrial Ecology.* **2011**, 15: 675-677.

(40) Wagner, M., & Llerena, P. Eco-innovation through integration, regulation and cooperation: Comparative insights from case studies in three manufacturing sectors. *Industry and Innovation.* **2011**, 18: 747-764.

(41) Horbach, J., Rammer, C., & Rennings, K. Determinants of Eco-innovations by type of environmental impact – the role of regulatory push/pull, technology push and market pull. *Ecological Economics*. **2012**, 78: 112-122.

(42) Deci, E. L., & Ryan, R. M. *Intrinsic motivation and self-determination in human behavior*. **1985**. New York: Plenum.

(43) Deci, E. L., & Ryan, R. M. The "what" and "why" of goal pursuits: Human needs and the self-determination of behavior. *Psychological Inquiry.* **2000**, 11: 227-268.

(44) Ryan, R. M., & Deci, E. L. An overview of self-determination theory: An organismic-dialectical perspective. In E. K. Deci, & R. M. Ryan (Eds.), *Handbook of self-determination research*, **2002**, 3-33. Rochester, NY: University of Rochester.

(45) Graves, L. M., Sarkis, J., & Zhu, Q. How transformational leadership and employee motivation combine to predict employee proenvironmental behaviors in China. *Journal of Environmental Psychology*. **2013**, 35: 81-91.

(46) Sawitri, D.R., Hadiyanto, H. & Hadi, S.P. Pro-Environmental Behavior from a Social Cognitive Theory Perspective. *Procedia Environmental Sciences*. **2015**, 23: 27-33.

(47) Robinson, M. A. An Empirical Analysis of Engineers' Information Behaviors. *Journal of the American Society for Information Science and Technology*. **2010**, 61(4): 640-658.

(48) Gladwin, T. N., Kennelly, J. J., & Krause, T.-S. Shifting paradigms for sustainable development: implications for management theory and research. *Academy of Management Review*. **1995**, 20(4): 874-907.

(49) Eccles, J. S. & Wigfield, A. Motivational beliefs, values, and goals. *Annual Review of Psychology*. **2002**, 53, 109-132.

Appendices

Appendix A – On-site Preliminary Interview Protocol (November 2017)

<u>I. INTRODUCTION</u>

Before we get into our discussion, I just wanted to ask a few background questions…

1. Background:
    a. How long have you been with Sherwin-Williams?
    b. What is your background (academic and/or professional)?

2. From your own perspective, please describe how sustainability fits into the mission and strategy at Sherwin-Williams?
    a. What value does it bring to the organization?
    b. Has sustainability been adopted into the employee culture at SW?
    c. What are the challenges that SW faces in the sustainability and product stewardship areas?

3. Current role at SW
    a. What responsibilities do you hold in your current role?
        i. How long have you been in this job?
        ii. Why did you pursue/take this job?
    b. What other jobs have you held at Sherwin-Williams?
    c. How does sustainability and product stewardship fit into your role?
        i. Specifically, environmental aspects?
        ii. Is sustainability or environmental performance considered in how you are evaluated?

4. Sustainability in your part of the organization
    a. What are the drivers for sustainability in your part of the organization?
    b. Are there any formal initiatives focused around these areas? (please describe)
    c. Are these areas a part of how employees in your division are evaluated?
    d. Is sustainability part of the culture?
        i. Success stories?
        ii. Challenges?

<u>II. KNOWLEDGE GENERATION</u>

Now I want to shift a little and talk about more specifically about the internal knowledge that Sherwin-Williams has in the sustainability and product stewardship areas …

5. Broadly speaking, what type of knowledge do you think is the most important to improve the sustainability and environmental performance of the organization?
    a. Is this knowledge that you were aware of before you started in this position?
    b. What has changed to make you more knowledgeable about environmental and sustainability areas since?
    c. How is this knowledge shared with you?
    d. How is this knowledge shared with other/all employees in your part of the organization?

6. Are some people at Sherwin-Williams more knowledgeable in sustainability than others?
    a. How are you aware of their knowledgeability on these topics?
    b. Do you think you have a pretty accurate idea of who knows the most about these areas in your part of the organization?
        i. Why?
        ii. Do you think other employees in your part of the organization are aware of the sustainability knowledge that these people hold?
    e. How do you think these individuals gained this specific kind of knowledge?
        i. What do you think are their incentives to care about sustainability in their roles?
    f. Are there any common characteristics that you would use to describe these individuals?

7. How do the knowledgeable people about sustainability at Sherwin-Williams communicate this information?
    a. Which channels do they use?
    b. How frequently?
    c. What kind of content?
    d. How is this information framed? (Jess can explain framing and give examples)

8. Do you share information about sustainability with employees in your part of the organization?
    a. Why?
    b. Who specifically do you share this kind of information with?
    c. What are any benefits of sharing this information?
    d. What are any challenges associated with sharing this information?
    e. How do you go about communicating this within your organization?

9. Looking at the other side, do you share information about sustainability with employees in other parts of the organization?
    f. Why?
    g. Who specifically do you share this kind of information with?
    h. What are any benefits of sharing this information?
    i. What are any challenges associated with sharing this information?

j. How do you go about communicating this within those outside of your organization?

10. Can you give a specific example of a recent time you shared sustainability information with someone (both inside and outside of your part of the organization)?

11. Do the groups whom you communicate with on sustainability topics differ from those you communicate with generally?
    a. Within your organization?
    b. Outside of your organization?

III. WRAP-UP

We are close to wrapping up, and I'd like to finish with some fun questions…

15. What is your favorite thing about working at Sherwin-Williams?
16. What are you most proud of in your part of the organization?
17. What do you envision for the future of sustainability at Sherwin-Williams?
18. Lastly, is there anything else you want to add?

I want to thank you for talking with me. What you told me was fascinating, and will be very helpful to me in my research. I appreciate the time you spent with me to discuss your work.

Appendix B – Full Survey Protocol (Administered March 2018)

This survey is intended to help the Company better understand how sustainability knowledge flows throughout [redacted] and, more specifically, how the communication of sustainability topics can be improved. The [redacted] group appreciates your response to help us improve our internal communication strategy.

The survey is voluntary and we encourage you to complete it during business hours. It should take approximately 5-10 minutes. The anonymity of your responses will be protected: no individual responses will be reported. Responses will only be reported in summary format.

If you have any questions regarding this survey, please contact [redacted] at [redacted] or at [redacted].

Thank you in advance for your participation.

Please answer the questions with sustainability defined as follows:

> *Sustainable products are those* products *that provide environmental, social and economic benefits while protecting public health and the environment over their whole life cycle, from the extraction of raw materials until the final disposal.* [redacted] *works to solve issues across the spectrum of the environment, safety, ethics, cost and performance while producing the best products in the industry. The* [redacted] *group is concerned with sustainability as it relates to* [redacted] *products, processes, materials, sourcing and people.*
>
> *The aggregated responses from this survey will be used internally by* [redacted] *and in a research study at the University of California, Santa Barbara (UCSB). The purpose of this research is to measure the flow of sustainability information across organizations. There are no risks to you in taking this survey, and your identity will not be shared with the UCSB research group.*

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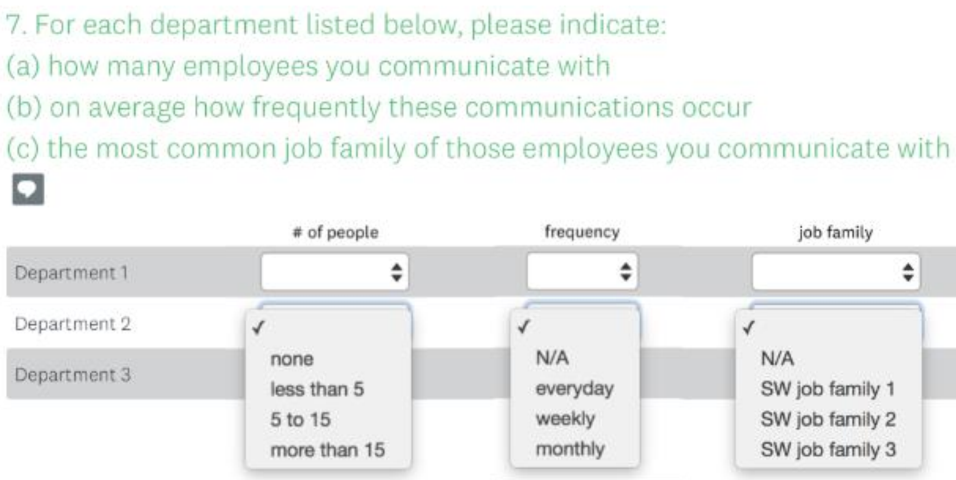
*DEMOGRAPHICS questions 1 – 6 were pre-populated for each employee.



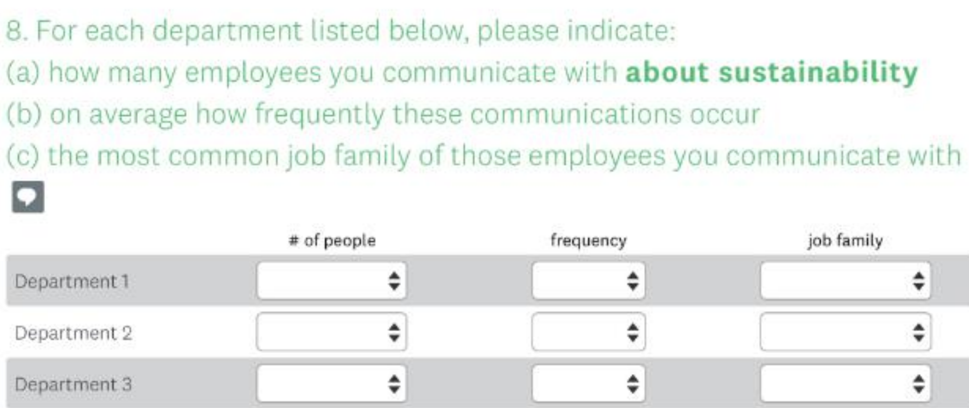
7. For each department listed below, please indicate:
(a) how many employees you communicate with
(b) on average how frequently these communications occur
(c) the most common job family of those employees you communicate with

	# of people	frequency	job family
Department 1			
Department 2			
Department 3			

# of people: ✓ none, less than 5, 5 to 15, more than 15

frequency: ✓ N/A, everyday, weekly, monthly

job family: ✓ N/A, SW job family 1, SW job family 2, SW job family 3



8. For each department listed below, please indicate:
(a) how many employees you communicate with **about sustainability**
(b) on average how frequently these communications occur
(c) the most common job family of those employees you communicate with

	# of people	frequency	job family
Department 1			
Department 2			
Department 3			

9. Do you seek out information about sustainability from sources outside of [redacted]? If yes, please select all that apply from the list below:

- Non-Governmental Organizations
- Academia
- Trade Associations/Publications
- Consultants
- News Outlets
- Online Sources
- Other______________

10. How do you think [redacted] external customers feel about having sustainability attributes associated with the [redacted] Brand?

- They care very much
- They care somewhat
- They are indifferent
- They do not care much

- They do not care at all
- I do not know how the customer feels about it

11. How do you think sustainability influences costs at [redacted]?
    - Greatly reduces costs
    - Slightly reduces costs
    - Does not influence costs
    - Slightly increases costs
    - Greatly increases costs
    - I do not know how it affects costs

12. How do you feel personally about sustainability in general?
    - It is very important to me
    - It is somewhat important to me
    - I am neutral about it
    - It is not very important to me
    - It is not important to me at all
    - I do not know how I feel

13. How clear do you think the meaning of sustainability is within [redacted]?
    - Very clear
    - Somewhat clear
    - Not very clear
    - Not clear at all
    - I am not familiar with sustainability at [redacted]

14. Please rank how you would like to receive future information about sustainability communications from [redacted] (drop-down with 1-5 rankings and 'N/A').
    - Webinars
    - Email Newsletters
    - In-person Workshops
    - [redacted] Page Updates
    - Other ________
    - I do not want to receive sustainability communications.

15. What is your preferred level of detail in the information you receive regarding sustainability?
    - A high level of detail
    - An overview - just enough to cover all the major information/trends
    - Just what is required of me by [redacted] to complete my job

16. How much uncertainty are you willing to tolerate in the information that you receive regarding sustainability? For example, a possible ban of a raw material being explored by regulators in the future.

- I want to know about everything, regardless of how it impacts my work
- I only want to know about things that are definitely going to impact my work
- I do not want to know about anything, regardless of how it impacts my work

17. Please write the names of any sustainability topics (if any) on which you would like to receive additional information from [redacted].

18. Please describe the kind of information or knowledge that you need/want to be able to address sustainability-related issues and objectives in your role.

19. Please provide other options on how you would like to receive future information about sustainability communications from [redacted].

20. If you have any other thoughts or recommendations for how [redacted] could do a better job communicating about sustainability, we encourage you to share them here.

Thank you for completing the survey. The [redacted] team greatly appreciates your feedback so that it can better serve the business as a strategic partner. If you have any questions regarding this survey, please contact [redacted] at [redacted] or at [redacted].