University of Michigan

DEFINING NEXT GENERATION SUPPLY CHAIN SUSTAINABILITY

from risk assessment perspective

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EXECUTIVE SUMMARY

INTRODUCTION

The importance of understanding supply chain sustainability is being realized by increasingly more people, including corporate managers, investors, policy makers, customers and other stakeholders. A lot of practitioners and academic researchers have addressed this issue in past few years.[1] However, most of their studies lack systematic thinking and are not quantifiable. Thus, a systematic and quantifiable model which incorporates economic, environmental and social factors is needed. In our study, a systematic and quantifiable risk assessment model based on the concept of “Triple Bottom Line” is developed in order to solve supply chain sustainability problem from risk assessment perspective.

ASSUMPTIONS AND METHODOLOGY

In particular, we divided the supply chain sustainability risk into three parts: operational risk, environmental risk and social risk. In our model, we assigned equal weights to these three risks.

For operational risk, we classified operational risk into four categories: supply risk, process risk, demand risk and corporate-level risk, which was simulating the processes along a supply chain and associated risks.

For environmental risk, we used Life Cycle Impact Assessment method to quantify the environment-related impact of the supply chain and convert the impact score to risk scores based on several assumptions.

For social risk, we used Global Social Index (GSI) and Global Governance Index (GGI) to identify the social risk for each location related to a certain sector along the supply chain. Then we introduced Global Supply Concentration (GSC) as weight of each location to calculate the social risk score of each sector.

[1] Ahi, Payman, and Cory Searcy. "A comparative literature analysis of definitions for green and sustainable supply chain management." Journal of Cleaner Production 52 (2013): 329-341.

CASE STUDY

We chose apparel and automotive industry to conduct case study as demonstration. The reason why we chose these two industries was that their supply chains have “deep” and “broad” structure respectively and might have different risks and risk-neutral strategies.

For apparel industry, supply chain mapping was conducted first (as shown in Figure ES1), followed by the calculation of each risk and finally the Risk Assessment Space visualization to identify the sector with highest supply chain sustainability risk (as shown in Figure ES2).

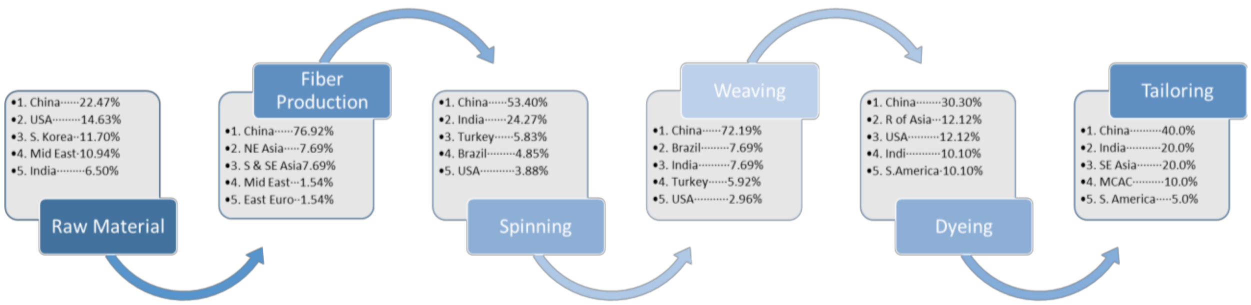

Figure ES1 Apparel Industry Supply Chain Mapping

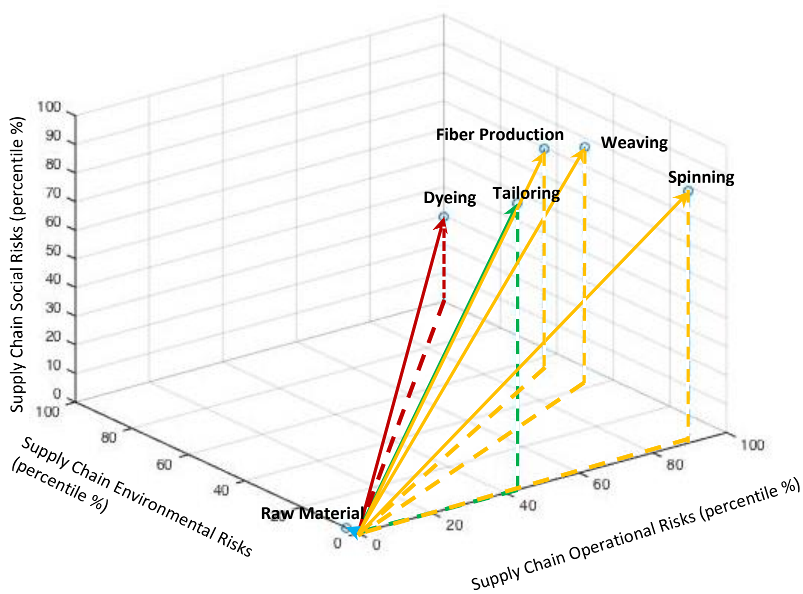

Figure ES2 Apparel Industry Risk Assessment Space

Based on the results above, we determined the sector of highest risk – Dyeing and suggested the strategy of increasing supply chain transparency due to the characteristics of apparel industry supply chain.

Furthermore, materiality analysis trying to decompose the supply chain sustainability risk into location-based and activity-based was conducted (as shown in Figure ES3). Different location-based and activity based risk-neutral strategies were also provided.

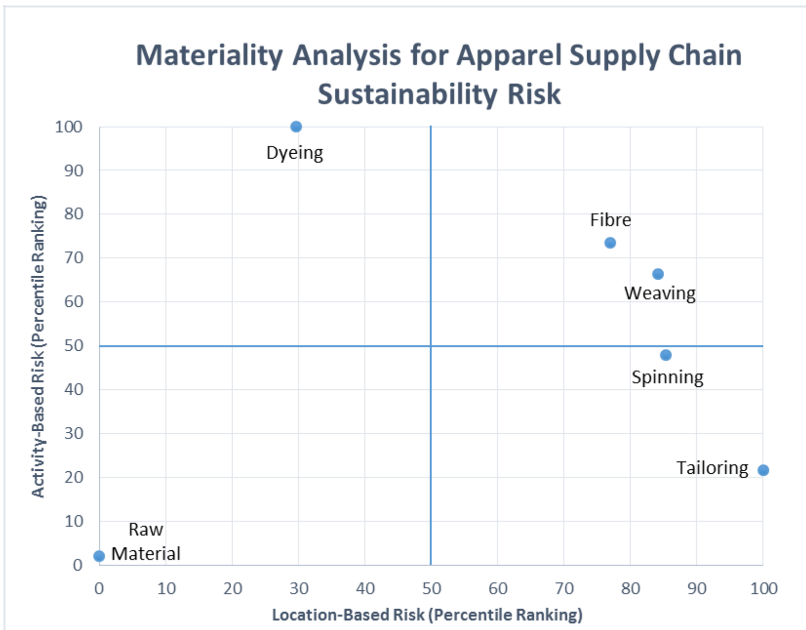

Figure ES3 Materiality Analysis for Apparel Supply Chain Sustainability Risk

For automotive industry, similar procedures were adopted to achieve the final result.

Figure ES4, Figure ES5 and Figure ES6 respectively presents the supply chain mapping, Risk Assessment Space and materiality analysis result for automotive industry. Compared with the case study of apparel industry, the difference was that the recommended strategy was to promote supplier auditing due to the nature of automotive industry supply chain.

Also, several location-based and activity-based risk-neutral strategies were provided.

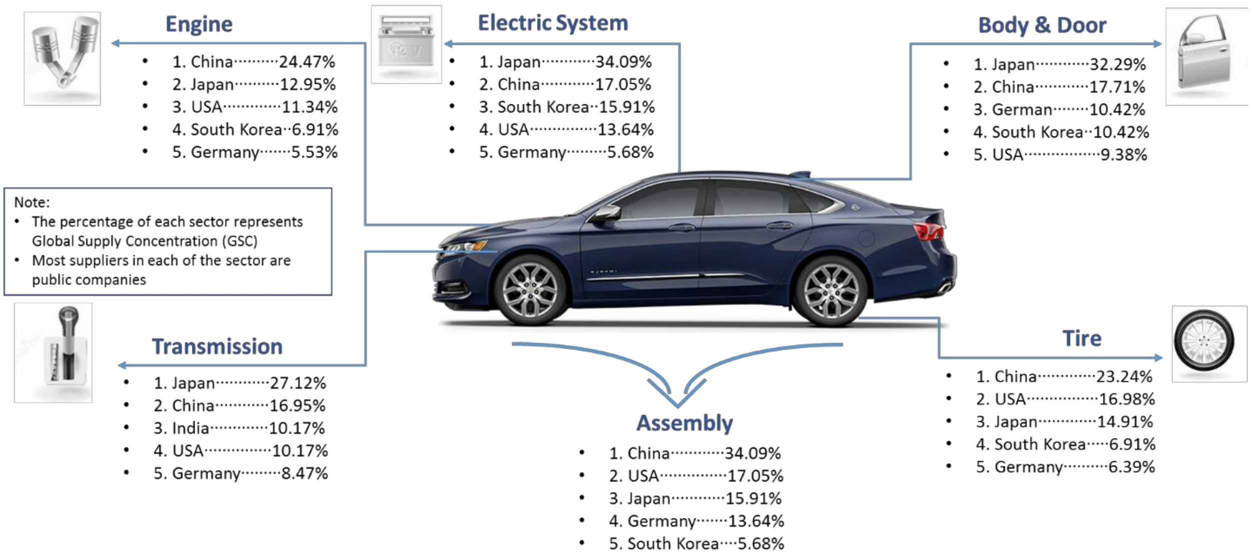

Figure ES4 Automotive Industry Supply Chain Mapping

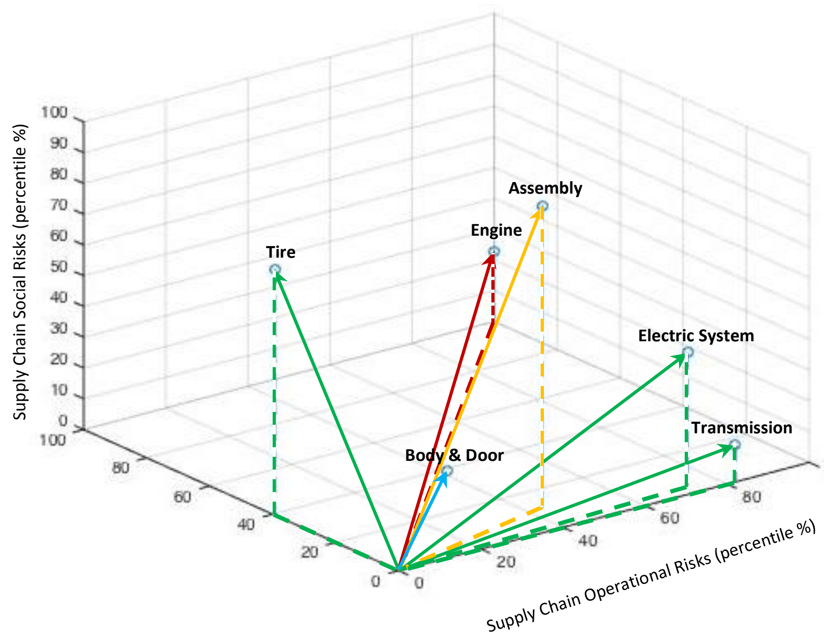

Figure ES5 Automotive Industry Risk Assessment Space

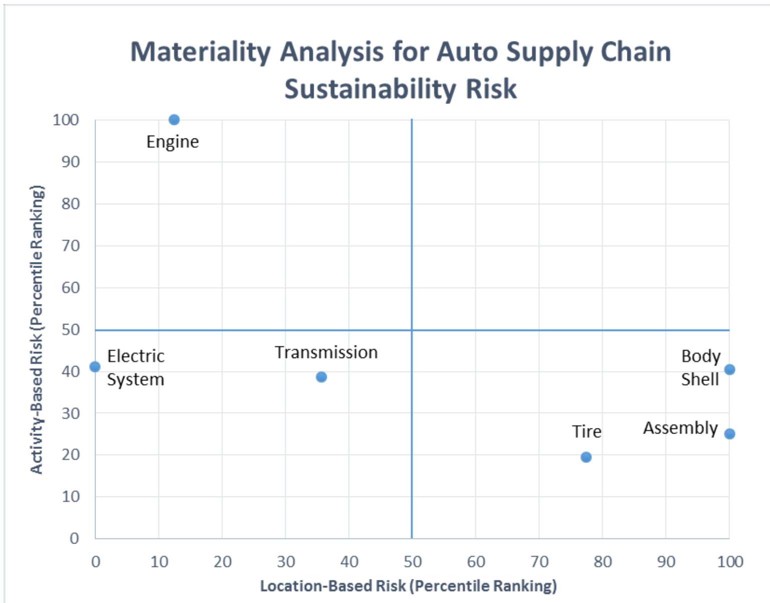

Figure ES6 Materiality Analysis for Auto Supply Chain Sustainability Risk

IMPLICATIONS AND CONCLUSION

We compared the difference between the two types of supply chain as indicated in the case study. Correspondingly, different risk-neutral strategies were also compared. Also, the possibility and suggested approaches of generalizing these two case studies to more similar industries were presented.

Meanwhile, what should be concerned about when the model is customized to corporate decisions was emphasized in terms of different prioritization, data and strategies. In addition, places to improve were also mentioned, including data availability & accuracy, transportation & time horizon and scope expansion.

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INTRODUCTION

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1 INTRODUCTION

Recently, sustainability has become a hot topic for business executives. Increasingly customers, investors, employees and other stakeholders want to know the environmental and social impacts of business activities. Managers would like to make more sustainable choices while avoiding loss of benefits. Thus, it is important that they make informed choices before making final decisions.

With growing globalization, the supply chain system has become more complex. To mitigate the potential sustainability risks, comprehensive evaluation and assessment tools should be developed to provide a deeper understanding of the associated risks and mitigating strategies.

Additionally, supply chain visibility is a key issue in today's corporate sustainability agenda. Multiple stakeholders are engaged in the supply chain across the globe. To promote supply chain transparency, quantifiable metrics should be used to identify the hotspots such as human health issue, human right and ecosystem quality along the supply chain.

The supply chain sustainability is based on the principle that "socially responsible products and practices are not only good for the environment, but are important for long-term profitability"[2]. The sustainability issues are receiving more attention among supply chain management. Researchers and practitioners have made progressive efforts in this promising area. In 1992, the report published by IISD (International Institute for Sustainable Development) had point out that "for the business enterprise, sustainable development means adopting business strategies and activities that meet the needs of the enterprise and its stakeholders today while protecting, sustaining, and enhancing the human and natural resources that will be needed in the future"[3]. The research conducted from 2002 to 2004 refined the discourse of corporate sustainability in order to meet the needs of its stakeholders. The concept is used to help stakeholders make better business decisions. (Dyllick and Hockerts, 2002, p. 131[4]; Van Marrewijk, 2003, p. 102[5]; Caldelli

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[2] http://searchmanufacturingerp.techtarget.com/definition/supply-chain-sustainability

[3] International Institute for Sustainable Development (IISD), 1992. Business Strategies for Sustainable Development. IISD, Winnipeg, Canada.

[4] Dyllick, T., Hockerts, K., 2002. Beyond the business case for corporate sustainability. Business Strategy and the Environment 11 (2), 130e141.

[5] Van Marrewijk, M., 2003. Concepts and definitions of CSR and corporate sustainability: between agency and communion. Journal of Business Ethics 44(2), 95e105.

and Parmigiani, 2004, p. 159[6]) One year later, Steurer et al. (2005) points out that the business (supply chain) sustainability should consider short-term and long-term economic, social, and environmental performance – known as the "Triple Bottom Line"[7]. After that, most definitions of business sustainability included those three performances.

Even though most of the definitions on supply chain sustainability include these three performances, the current study primarily discussed supply chain sustainability at corporate level, focusing more on environmental risks in particular. For example, Fiksel (2010) used LCA as the method to evaluate in supply chain sustainability. [8] Fransoo (2014) also considered environmental sustainability, but sought to balance the economic, social and environment performances as well.[9]

For our study, a more well-rounded approach is adopted to better capture the core value of sustainability. Our study is conducting a systematic evaluation, focusing on the so-called "Triple Bottom Line" based on all three risks assessment, including environmental risk, operational risk and social risk.

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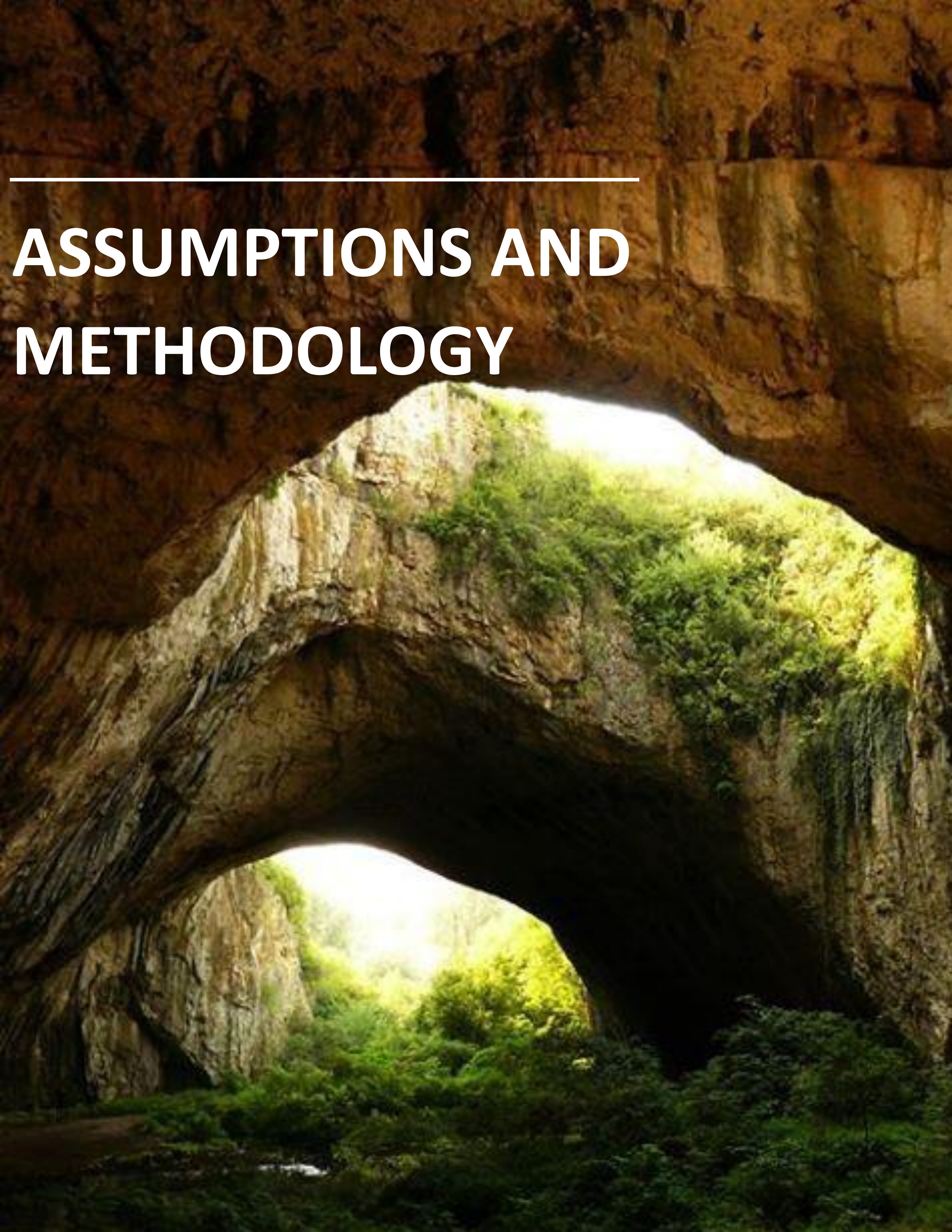
[6] Caldelli, A., Parmigiani, M.L., 2004. Management information system e a tool for corporate sustainability. Journal of Business Ethics 55 (2), 159e171.
[7] Steurer, R., Langer, M.E., Konrad, A., Martinuzzi, A., 2005. Corporations, stakeholders and sustainable development I: a theoretical exploration of business-society relations. Journal of Business Ethics 61 (3), 263e281.
[8] Fiksel, Joseph. "Evaluating supply chain sustainability." Chemical Engineering Progress 106.5 (2010): 28-38.
[9] Fransoo, Jan C., Hans-Otto Günther, and Werner Jammernegg. "Environmental sustainability in supply chains." Flexible Services and Manufacturing Journal 26.1-2 (2014): 1-4.

ASSUMPTIONS AND METHODOLOGY



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2 ASSUMPTIONS AND METHODOLOGY

As indicated in the last part of background, the objective of this study was to develop a systematic approach which could assess next generation supply chain sustainability (SCS). To quantify the performance or the potential problem of supply chain sustainability, we decided to build a quantifiable risk assessment model to address this issue.

In our study, the concept of "Triple Bottom Line" is applied in order to assess the next generation supply chain sustainability. Therefore, our model decomposed supply chain sustainability risk into three parts: Operational Risk, Environmental Risk and Social Risk. In this part, the methodology and relevant data of each part is introduced.

Before we go into details, we would like to claim that 1) the word "supply chain" in our model includes only raw material production, manufacturing and production; 2) our model assigned equal weight to the "Triple Bottom Line"; 3) the operational risk and environmental risk in our model was considered as controllable risks by the industry itself; 4) the social risk in our model referred to the external societal factors which are regarded as uncontrollable.

2.1 Operational Risk (OR)

Based on the idea of Sodhi, ManMohan S. et al. (2012)[10], the operational risk along a supply chain is multifaceted. Companies have different groups facing the supply side (i.e., purchasing), those working in internal processes (manufacturing, storage and internal distribution), and those facing the demand side (distribution and sales). Besides, corporate-level operations facilitate these processes. Therefore, our model included four types of operational risk (as shown in Table 1):

- Supply Risks
- Process Risks
- Demand Risks
- Corporate-level Risks

[10] Sodhi, ManMohan S., Tang, Christopher S. "Managing Supply Chain Risk." International Series in Operations Research & Management Science. Vol. 172 (2012).

Table 1 Supply Chain Operational Risk Classification

Supply Risks	Process Risks	Demand Risks	Corporate-level Risks
- Supplier failure - Supply commitment - Supply cost	- Design - Yield - Inventory - Capacity	- Forecasting - Change in technology or in consumer preference - Receivable	- Financial - Supply chain visibility - IT systems - Intellectual property - Exchange rate

2.1.1 Supply Risks

Supply risks pertain to risk events on the supply side that include supplier defaults or other unexpected changes in supply cost, delivery, quality or reliability. Consider the following types of risks on the supply side:

Supplier failure. This metric is evaluating the possibility and potential impacts if suppliers run out of business or fail to supply. The possibility is evaluated by the market structure (segmented/concentrated) of the sector that suppliers are in and if some suppliers could exercise their market power (competitive/monopoly/oligopoly). The potential impacts are derived from the cost structure of the product and whether there are existing substitutes.

Supply commitment. This metric is evaluating whether buyers in the sector have long-term contracts or commitment with suppliers and the benefit (risk) with (without) the commitment. The sales model (commodities/retail/contract) is used to draw the conclusion.

Supply cost. This metric is evaluating the possibility and potential impacts if there is a volatility in acquisition costs. The possibility is determined by historical price information and supply/demand data. Also, the assessment of bargain power of buyers is involved in the analysis. The potential impacts are derived from the cost structure of the product and whether there are existing substitutes.

2.1.2 Process Risks

Process risks pertain to risks within the sector's internal supply chain, typically pertaining to design, manufacturing and distribution. Consider the following categories of supply-chain risks:

Design. This metric is evaluating the possibility and potential impacts if there is faulty design or manufacturing. It is evaluated by the historical performance (events of recall/poor quality) and the implementation of Total Quality Management, Lean Manufacturing and Six Sigma across the sector.

Yield. This metric is evaluating the possibility and potential impacts if the yields are not able to match to the demand. It is evaluated by the historical performance (fall short of demand) and the overall planning and operations across the sector.

Inventory. This metric is evaluating the possibility and potential impacts if there is excess or inadequate inventory. Excess or inadequate inventory could hurt both financial and operational performance. It is evaluated by the average inventory turnover ratio across the sector compared to similar sectors.

Capacity. This metric is evaluating the possibility and potential impacts if there is a excess or inadequate capacity. Inadequate capacity means a company may be unable to meet its demand and thus suffer from unmet demand, while excess capacity is a symbol of lacking efficiency and thus diminish profitability. It is determined by the average capacity utilization rate across the sector compared to similar sectors.

2.1.3 Demand Risks

Demand risks pertain to risks facing demand side that include bad forecasting or potential new technology or substitutes. Consider the following categories of supply-chain risks:

Forecasting. This metric is evaluating the possibility and potential impacts if there is mismatch between forecasting and actual demand. It is evaluated by the historical performance (historical forecasting vs actual demand).

Change in technology or in consumer preference. This metric is evaluating the possibility and potential impacts if new technology is scaled up in the market or consumer preference is altered to substitutes. It is evaluated by the adoption rate of potential new technologies and market trends.

Receivable. This metric is evaluating the possibility and potential impacts if there is delayed receivables. Poorly managed receivables could hurt both financial and operational performance. It is evaluated by the average receivable turnover ratio across the sector compared to similar sectors.

2.1.4 Corporate-level Risks

Corporate-level risks pertain to specific risks related to companies within the sector. Consider the following categories of supply-chain risks:

Financial risk. This metric is evaluating the possibility and potential impacts if there are liquidity issues that lead to financial distress. It is evaluated by the average liquidity ratios (current ratio/working capital) and leverage ratios (D/E ratio) across the sector compared to similar sectors.

Supply chain visibility. This metric is evaluating the possibility and potential impacts if law suits or contingencies occur because of supply chain visibility issues. It is evaluated by whether there are existing organizations or campaigns of supply chain visibility within the sector.

IT systems risk. This metric is evaluating the possibility and potential impacts if the IT systems break down. It is evaluated by the sector's reliability on IT systems and whether the IT systems are stable historically.

Intellectual property. This metric is evaluating the possibility and potential impacts of loss of intellectual property or compliance costs related to intellectual property. It is evaluated by the proportion of intellectual property is involved in the products. Also, historical number of law suits and the intellectual property law within the sector help to draw the conclusion.

Exchange rate. This metric is evaluating the possibility and potential impacts of change in exchange rate. It is evaluated by whether the sector is involved in multi-national or regional businesses.

2.1.5 Operational Risk Assessment Matrix

Potential impacts were labeled from negligible to catastrophic and numbered from 1 to 10 in the same order to identify the magnitude of the risk. The probability was labeled from rare to certain and labeled alphabetically. This method provided an easy way to identify the level of risk both graphically and in text. For example, a risk identified as a category 5A would be recognized as having catastrophic impacts and an almost certain likelihood of happening. Correspondingly, a risk labeled 1E could been easily seen as nothing to worry about. As shown in Table 2, the darker the color of the cell was, the greater the risk would be. Particularly, the darkest group is scored by 100 indicating the highest risk, while the lightest group is scored by 0 indicating the lowest risk. Scores of all other groups are evenly distributed with the interval of 25.

Table 2 Supply Chain Operational Risk Assessment Matrix

Impacts / Probability	Negligible	Minor	Moderate	Major	Catastrophic
>90% (almost certain)	1A	2A	3A	4A	5A
50-90% (likely)	1B	2B	3B	4B	5B
30-50% (moderate)	1C	2C	3C	4C	5C
10-30% (less likely)	1D	2D	3D	4D	5D
<10% (unlikely)	1E	2E	3E	4E	5E

2.2 Environmental Risk (ER)

To evaluate supply chain environmental impact, the Environmental Indicator (EI) established an evaluation model based on life cycle inventory analysis and life cycle impact assessment. Life cycle assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product's life-cycle: raw material production, manufacturing, transportation, usage, and end-of-life[11]. We assumed that the environmental impact of the supply chain comes mainly from raw material production and manufacturing phases of the full life cycle. As a result, our model did not include the use phase or end-of-life stage into the metric.

[11] International Standard Organization. ISO 14044 International Standard: Environmental Management – Life Cycle Assessment – Requirements and Guidelines, Geneva, Switzerland (2006)

2.2.1 Functional Unit

Unlike the traditional life cycle assessment where an actual product is always set as the functional unit, EI assumed an "Average Product" with average industrial material input, output, and technology based on previous supply chain mapping. In this way, EI established a product based functional unit which could represent the whole supply chain.

2.2.2 Life Cycle Inventory Analysis

As mentioned before, our study focused on raw material production and manufacturing phases, thus "cradle to gate" was chosen as the scope of study. The data required in life cycle inventory analysis were aimed at creating material and energy flow of the "Average Product", including

- Raw material from both artificial and natural resources
- Manufacturing and assembly processes
- Energy and water usage for the original equipment manufacturers (OEM)
- Any possible emission / discharge into the environment

2.2.3 Life Cycle Impact Assessment and risk score conversion

EI referred to ReCiPe end point method from the ecoinvent inventory data for the environmental impact assessment. The method consisted of three different damage categories of associated weighting: Human Health (40%), Ecosystem Quality (40%), and Resources (20%). To convert the ReCipe points into a 0-100 risk score, EI assigned the risk score of 100 to the sector as shown in Equation 2-1. i indicates a random sector in the supply chain, and n indicated total number of selected sectors in the supply chain mapping.

$$ER_i = {}^{ReCiPe_i}\Big/_{Max\ (_1^nReCiPe)} \times 100 \qquad (2\text{-}1)$$

2.3 Social Risk (SR)

Modern supply chains go through different locations across the world. The society and governance of a location largely determines the social risk at that location as part of the supply chain. Thus, understanding the social risk along a supply chain is crucial to assessing supply chain sustainability risk.

To assess the social risk for one segment along supply chain, our model decomposed the assessment into two parts. One is the risk score for a single location, and the other is the proportional contribution of the location.

2.3.1 Risk Assessment for One Location

In our model, we used two indices to assess the social risk. One is Global Social Index (GSI) indicating society-related issues. The other one is Global Governance Index (GGI) measuring governance-related issues. We assigned equal weight to both indices and we take the sum of GSI and GGI to get social risk score.

2.3.3.1 Global Social Index (GSI)

For Global Social Index, we consulted to the SOCIAL HOTSPOTS's classification system. However, there existed several overlapping indicators with GGI. As a result, we decided to ignore these indicators and put them into GGI. We assigned equal weight to each of the 10 indicators and each indicator was scored from 0 to 100. The total score for each sector was calculated as the multiplication of its weight with its score. Thus, the GSI for one location was the sum of the total score for each indicator. Table 3 shows how we calculate GSI in detail.

Table 3 Global Social Index Breakdown

Social Categories		Weight	Score	Total Score
Labor Right and Decent Work	Child Labor	0.1	S1	weight * score
	Forced Labor	0.1	S2	weight * score
	Excessive Working Time	0.1	S3	weight * score
	Unemployment	0.1	S4	weight * score
Occupational Health & Safety	Injuries and Fatalities	0.1	S5	weight * score
	Toxics and Hazards	0.1	S6	weight * score
Human Rights	Gender Inequality	0.1	S7	weight * score
	Human Health Issues	0.1	S8	weight * score
Community Infrastructure	Drinking Water	0.1	S9	weight * score
	Sanitation	0.1	S10	weight * score
GSI for one location		Sum of Total Score		

Child Labor and Forced Labor. For these two indicators, we used the data from Verisk Maplecroft. As shown in Table 4, we converted the categorical information on the index map to quantitative risk scores ranging from 0 to 100.

Table 4 Child Labor and Forced Labor Score Conversion Rubric

Categorical Information	Extreme	High	Medium	Low	No Risk
Quantitative Risk Score	100	75	50	25	0

Excessive Working Time. To assess the risk associated with excessive working time, we compared the actual working time (International Labor Organization) with the limited working time (International Labor Office). As shown in Figure 1, high limited working time and high actual working time indicates the highest risk, while low working time and low actual working time indicates lowest risk.

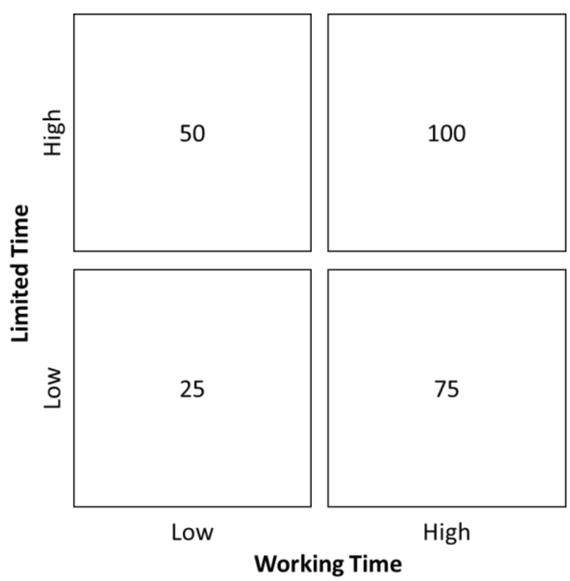

Figure 1 Excessive Working Time Assessment Matrix

Unemployment. We used unemployment rate of each location (International Labor Office) as an indicator to assess the risk of unemployment. We normalized the highest unemployment rate to 100 and lowest to 0 to get the percentile score.

Injuries and Fatalities. We used the fatality rate (per 100,000 workers) and accident rate (per 100,000 workers) data from the article "Global estimates of occupational accidents"[12] to evaluate the risk of injuries and fatalities. Similarly, we normalized these two rates to percentile scores and take equal weight of them to get the risk score associated with injuries and fatalities.

Toxics and Hazards. To assess the risk associated with toxics and hazards, we synthesized the data from UNSD/UNEP, Eurostat Environmental Data Centre on Waste and OECD Environmental Data Compendium.

We transformed the original categorical waste generation amount data into percentile score, as shown in Table 5.

Table 5 Toxics and Hazards Score Conversion Rubric

Waste Generation Amount	**30,001 - 141,020**	**10,001 - 30,000**	**5,001 - 10,000**	**1,001 - 5,000**	**0 - 1,000**
Risk Score	100	75	50	25	0

Gender Inequality. For Gender Inequality, we used the "Gender Inequality Index" data from Human Development Report Team. We normalized the original index figure into percentile score.

Human Health Issue. We measured the risk of human health issue by the proportion of health expenditure in total GDP from World Bank database. The country with higher health expenditure in total will have a lower risk because the residents in the country will have more guarantees on health issues. Also, the proportion number was normalized into percentile score.

Drinking Water and Sanitation. For drinking water and sanitation, we used the data from the Environmental Performance Index (EPI). For EPI, the country with a lower risk will have a higher score, in order to make the score consistent with the rest of our metrics, we took the residual of the original score from 100 as our risk score of drinking water and sanitation.

[12] Hämäläinen, Päivi, Jukka Takala, and Kaija Leena Saarela. "Global estimates of occupational accidents." Safety Science 44.2 (2006): 137-156.

2.3.1.2 Global Governance Index (GGI)

Geopolitical factor has a relatively high probability of causing disruptions within global supply chains (expressed by a survey of 400 executives performed by the World Economic Forum and Accenture). Therefore, governmental policies, actions, and stability can significantly impact supply chain risks. The indicator of the Global Governance Index (GGI) composed by five of the worldwide governance indicators (WGI)[13] was adopted to quantify this impact.

The WGI is utilized to quantify this risk and had been used in previous criticality assessments (e.g. European Commission[14] and Graedel, T. E. et al.[15]). In the WGI methodology, six different indices were included, each based on a number of different data sources. In each index, the data were standardized and a percentile ranking is given for each country or region.

For the purposes of this study, Political Stability and Absence of Violence/Terrorism (PV), Government Effectiveness (GE), Regulatory Quality (RQ), Rule of Law (RL), and Control of Corruption (CC) were shortlisted, which are regarded as the most critical factors of governance influence on supply chain, as shown in Figure 2. However, in the scoring system of WGI, the country with a lower risk will have a higher score. In order to make the score consistent with the rest of our metrics, we took the residual of the original score from 100 as our risk score. Finally, GGI is the average of the five component scores.

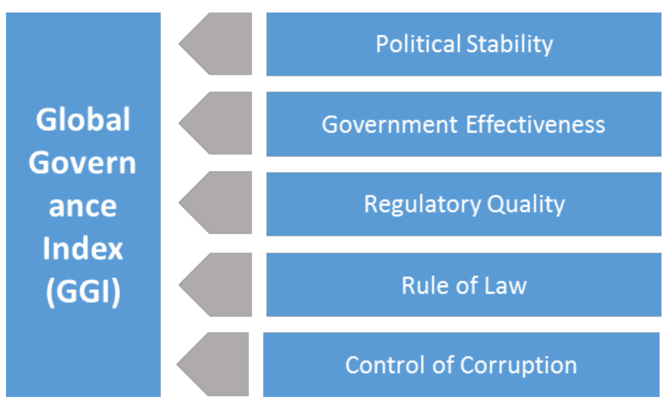

Figure 2 Global Governance Index Breakdown

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[13] Kaufmann, D.; Kraay, A.; Mastruzzi, M. The Worldwide Governance Indicators, Methodology and Analytical Issues; World Bank Policy Research Working Paper No. 5430; World Bank: Washington, DC, 2010.
[14] European Commission (EC). Critical Raw Materials for the EU. Report of the Ad-Hoc Working Group on Defining Critical Raw Materials; EC: Brussels, Belgium, 2010.
[15] Graedel, T. E. et al. Methodology of Metal Criticality Determination. Environmental Technology & Science. 2012.

2.3.2 Proportional Contribution of One Location

As mentioned before, for a sector along a supply chain, all the manufacturing and production processes take place in various countries or regions. Some sectors are predominantly concentrated in only a few areas, while others are more widely dispersed worldwide. In general, the more concentrated the distribution of a segment in one location, the more impact this location have on this segment.

We adopted the Global Supply Concentration (GSC) to quantify the proportional contribution of one location to the sector. It is implemented with the estimated global supply shares.

2.3.3 Social Risk Calculation for One Sector

To obtain the social risk score for one sector along a supply chain, the first step is to calculate the social risk score for each location related to the sector by combining GSI and GGI. Then, using GSC in one sector, allocate corresponding weights to different locations. The last step is to add up all locations' weighted social risk scores to get the social risk score for the sector. The calculation process is expressed by Equation 2-2.

$$SCSR_{Sector_i} = \sum_{j=1}^{n} [(\frac{1}{2} \times GSI_{location\ j} + \frac{1}{2} \times GGI_{location\ j}) \times GSC_{location\ ij}] \quad (2\text{-}2)$$

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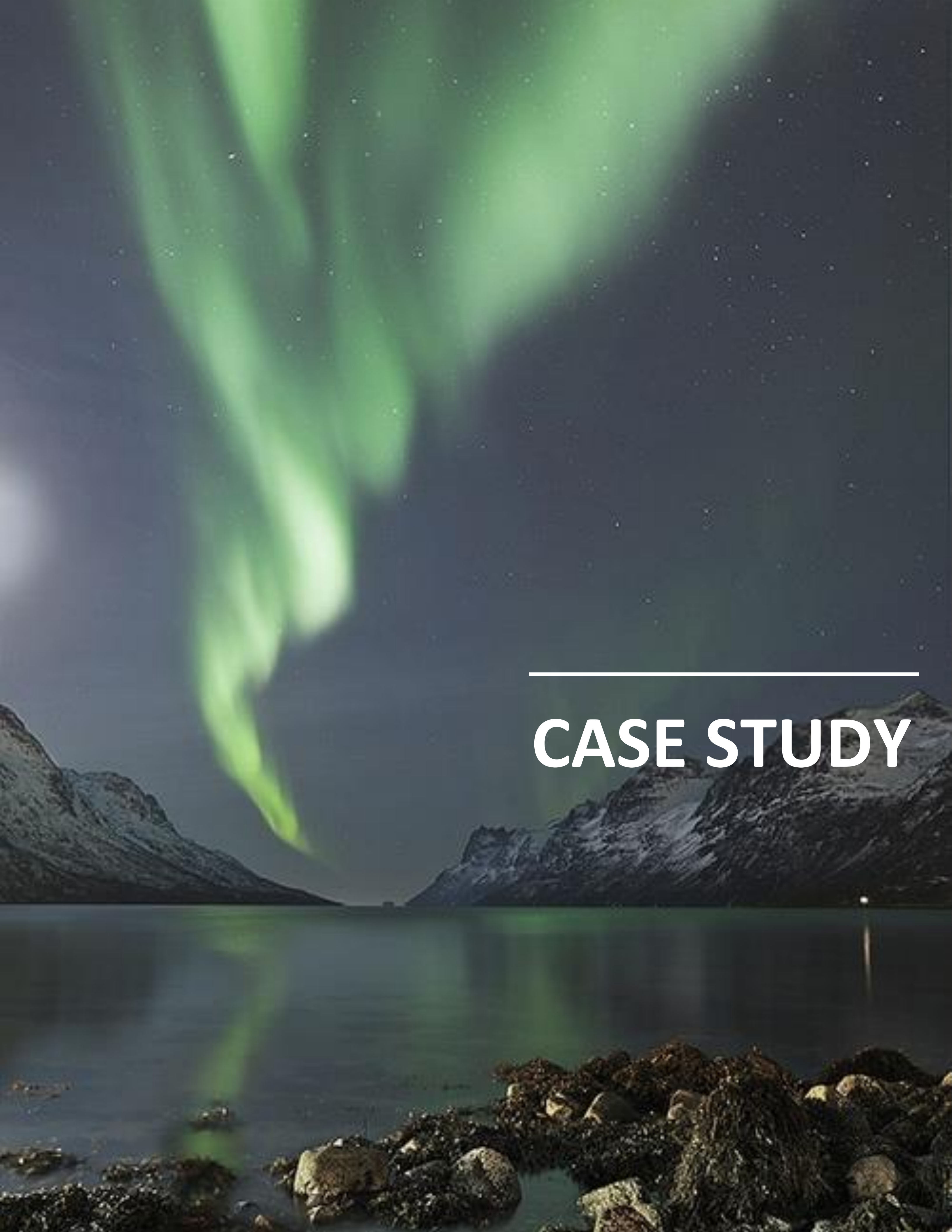

CASE STUDY

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3 CASE STUDY

To demonstrate our risk assessment system of supply chain sustainability, two case studies for two different industries were presented in this part.

3.1 Supply Chain Selection

The structure of a supply chain is usually determined by the final product structure. As for product structure, deep structure and broad structure are the two main categories. Deep structures arise as a result of numerous sub-stages in acquisition of materials and components, and manufacturing and assembly/final manufacture, while broad structures mean that many items must be available simultaneously for the initiation of manufacturing at higher structural levels.[16]

In our case study, apparel industry was selected as the representative of supply chain with deep structure, while automotive industry was selected as the representative of supply chain with broad structure.

3.2 Case Study of Apparel Industry

In the case study of apparel industry, the first step was to conduct supply chain mapping, followed by sustainability risk assessment and analysis.

3.2.1 Supply Chain Mapping

While mapping the supply chain of apparel industry, six sectors were selected as the representative of a simplified supply chain. They were raw material production, fiber production, spinning, weaving and tailoring based on as several industry reports and academic literature related to apparel supply chain sustainability (e.g. Bruce et al.[17], Jin[18]).

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[16] Logistics and Supply Chain Structure. McGraw Hill Higher

[17] Jin, Byoungho. "Performance implications of information technology implementation in an apparel supply chain." Supply Chain Management: An International Journal 11.4 (2006): 309-316.

[18] Bruce, Margaret, Lucy Daly, and Neil Towers. "Lean or agile: a solution for supply chain management in the textiles and clothing industry?." International journal of operations & production management 24.2 (2004): 151-170.

When mapping the global apparel supply chain, determining the global supply concentration (GSC) was the main part of the supply chain study, due to its essential role of helping to understand the global supply chain structure and assess the social risk. The GSCs in sectors of raw material, fiber production, spinning, weaving, dyeing and tailoring were determined based on the relevant data from the Cotton Incorporated[19], IHS Chemical[20], Textile World[21][22] and Chemical Engineering & Process Technology[23].

In each case, the proportional production or consumption of each country or region was assumed as its GSC. As rule of thumb, we first considered proportional production in each country or region as the GSC since supply chain activities are more concerned about production rather than consumption. Whenever production data is not available, we would turn to consumption data as a proxy for consumption data.

Particularly, for raw material sector, the GSC was the weighted average GSC by the consumption of different raw materials in world apparel industry, which was consistent with same idea of the formerly mentioned "Average Product".

Figure 3 shows the main results of global apparel supply chain mapping. (Find more details in Appendix B)

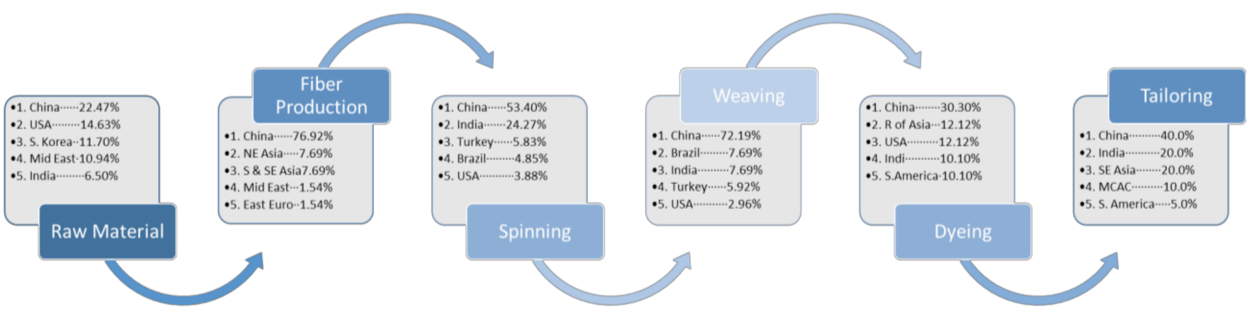

Figure 3 Apparel Industry Supply Chain Mapping

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[19] Cotton Incorporated, Monthly Economic Letter, 2015
[20] IHS, Xylenes - Chemical Economics Handbook (CEH), 2013
[21] Textile World, Textile Manufacturing: Global Cost Trends From A U.S. Perspective: Weaving
[22] Textile World, Textile Manufacturing: Global Cost Trends From A U.S. Perspective: Staple Spinning
[23] Ghaly AE, Ananthashankar R, Alhattab M, Ramakrishnan VV (2014) Production, Characterization and Treatment of Textile Effluents: A Critical Review. J Chem Eng Process Technol 5:182. doi: 10.4172/2157-7048.1000182

3.2.2 Operational Risk Assessment

The operational risk of apparel industry's supply chain is listed as follows:

Table 6 Apparel Industry Supply Chain Operational Risk Score by Sector

Sector	Operational Risk Score
Raw Material Production	22.71
Fiber Production	33.29
Spinning	33.29
Weaving	33.29
Dyeing	34.17
Tailoring	27.67

As shown in Table 6, dyeing had the highest operational risk score among all of the sectors, while raw material production had the lowest. Also, fiber production, spinning and weaving showed second highest score.

Table 7 Apparel Industry Supply Chain Operation Risk Score Breakdown by Sector

Sector	Supply Risks	Process Risks	Demand Risks	Corporate-level Risks
Raw Material Production	2.00	1.75	2.33	3.00
Fiber Production	5.67	2.25	2.00	3.40
Spinning	5.67	2.25	2.00	3.40
Weaving	5.67	2.25	2.00	3.40
Dyeing	4.67	1.00	4.00	4.00
Tailoring	3.33	1.00	3.33	3.40

**Note: The fiber production, spinning and weaving shares the same operational risks in this case study.*

Digging deeper into the detail, we could find out that the reason why dyeing has the highest operational risk comes from its highest demand risks and corporate-level risks, as shown in Table 7. If we further break down the factors, we could find out that dyeing has high risks in demand forecasting and change in consumer preference. To be specific, consumers tend to switch their preference in apparel industry and demand forecasting is usually hard in apparel industry. Additionally, dyeing had very high supply chain visibility risks since there have not been large-scale associations or organizations addressing the supply chain problems of dyeing sector.

3.2.3 Environmental Risk Assessment

3.2.3.1 System Boundary

As we mainly focused on creating a model based on "Triple Bottom Line" for the supply chain sustainability, the study embraced analytical framework of life cycle assessment with cradle to gate as its system boundary for the "Average Product".

Based on the supply chain mapping, the process in the assessment includes raw material production, fiber production, spinning, weaving, dyeing, and tailoring. Packaging and transportation was not included in the assessment process, while the analysis could be potentially improved by involving the modeling of these two stages.

3.2.3.2 Functional Unit

The "Average Product" for apparel industry is defined as the integration of mainstream textile materials and manufacturing process in the sector. It should be clarified that unlike a normal wearable cloth, the "Average Product" is the abstract of industrial representatives. As indicated by the previous supply chain mapping, fiber as the primary material in the textile industry was assessed in the "Average Product".

The study focused primarily on fiber as the main raw material, followed by manufacturing processes of fiber production, spinning, weaving, dyeing, and tailoring based on the supply chain mapping. Assuming a weight of 0.6 kg in an average textile product, the raw material consumed for the "Average Product" was based on market share of world fiber consumption in textile sector shown in Table 8.

3.2.3.3 Cradle to gate Inventory

(1) Raw material

Based on the assumption in the functional unit, the raw material inventory was listed in Table 8.

Table 8 Raw Material Inventory for the "Average Product" in Apparel Industry

Raw Material	World Total Consumption (m tons)	Percentage	Weight of the "Average Product" (kg)	Weight of the Raw Material (kg)
Cotton	22940.51	32.90%		0.1974
Wool	1464.29	2.10%		0.0126
Flax	697.28	1.00%	0.6	0.0060
Cellulosic Fibers	2719.39	3.90%		0.0234
Synthetic Fibers	41906.53	60.10%		0.3606

(2) Fiber production, spinning, weaving, and dyeing

The case analysis utilized ecoinvent database for these processes based on the mass of the raw materials.

(3) Tailoring

To simplify the analysis, we assumed that the main input for the tailoring process was water and electricity. Based on the publicly available water consumption and carbon emission data from the corporate social responsibility reports,[24, 25] we calculated the water and electricity consumption per cloth. For the electricity intensity (kWh / cloth) of the apparel industry, we estimated world's average carbon intensity based on its combination of energy source and associated carbon intensity (See Appendix B). The electricity intensity of the apparel industry was estimated using Equation 3-1. Similarly, water intensity (L / cloth) was estimated using Equation 3-2. (Find detailed assumptions and data in Appendix B)

[24] "H & M Conscious Actions Sustainability Report 2013." *H & M*. Web. 6 Apr. 2015.
[25] "Gap Inc. 2011/2012 Social & Environmental Responsibility Report." *Gap Inc.* Web. 6 Apr. 2015.

$$E_i = {E_{tailoring}}\Big/{Sales_{\#}} = {\frac{C_{total} \times P}{I_{ele}}}\Big/{\frac{Sales_{Ann}}{P_i}} \tag{3-1}$$

$$W_i = W_{app} \times Weight_{app} \tag{3-2}$$

3.2.3.4 Environmental impact and Environmental Risk Score

Based on the ecoinvent database, we applied ReCiPe 2008 life cycle impact assessment method, an end-point assessment involving categories of human health (DALY), ecosystem quality (species.yr), and resource depletion ($).

The method gave enough broadness and comprehensiveness to evaluating the systematic environmental impact across the supply chain. It was worth mentioning that due to most of our data came from publicly available sources, the assumptions and result may vary.

Because the ReCiPe score illustrated relative environmental impact of the sectors across apparel supply chain, we assumed that the environmental risk positively correlates with environmental impact. The conversion of ReCiPe scores was based on Equation 1. Table 9 shows the ReCiPe scores and environmental risk scores for the apparel supply chain.

It can be seen from the Table 9 that Dyeing has the highest environmental risk along the apparel supply. The main contributor of the dyeing sector environmental risk mainly came from the water pollution of dye usage which resulted into the highest human health, ecosystem quality, and resource depletion risks. Electricity contributed the most to the environmental risks of fiber production and weaving sections, the second and third highest environmental risk sectors across the supply chain.

The processes yielded relative significant impact on climate change human health compared to other end-point risk categories, which correspond to the current industrial initiatives to reducing greenhouse gas emissions (more details in Appendix B).

Table 9 LCIA and Environmental Risk Score of Apparel Supply Chain

Sector	Weighted ReCiPe Score	Environmental Risk Score	Environmental Risk Score Breakdown	
Raw Material	0.18	12.92	Human Health	4.97
			Ecosystem Quality	3.20
			Resources Depletion	4.76
Fiber Production	0.83	58.81	Human Health	26.68
			Ecosystem Quality	14.08
			Resources Depletion	18.05
Spinning	0.18	12.40	Human Health	6.21
			Ecosystem Quality	2.69
			Resources Depletion	3.50
Weaving	0.65	45.85	Human Health	23.48
			Ecosystem Quality	10.03
			Resources Depletion	12.33
Dyeing	1.42	100.00	Human Health	40.53
			Ecosystem Quality	36.00
			Resources Depletion	23.47
Tailoring	0.13	9.25	Human Health	3.99
			Ecosystem Quality	1.91
			Resources Depletion	3.34

3.2.4 Social Risk Assessment

As mentioned in the methodology of social risk assessment, the first step was to assess the social risk for one location. In this case study, every location related to the apparel industry was assessed through the social risk assessment system first.

According to the results of supply chain mapping from global industry perspective, there were mainly 23 countries or regions evolved in the global supply chain. As they were assessed by the same processes, only the assessment of one location is taken as a demonstration sample in detail. Due to the importance of China in global apparel industry, China was selected as the representative location.

3.2.4.1 Global Social Index (GSI)

The GSI of China was calculated by aggregating four main parts: labor right & decent work, occupational health & safety, human rights and community infrastructure, as shown in Table 10.

Table 10 China Global Social Index Breakdown

Social Categories		Weight	Score	Total Score
(Internal) Labor Right and Decent Work	Child Labor	0.1	100	10
	Forced Labor	0.1	100	10
	Excessive Working Time	0.1	75	7.5
	Unemployment	0.1	27.61	2.761
Occupational Health & Safety	Injuries and Fatalities	0.1	44	4.4
	Toxics and Hazards	0.1	75	7.5
(External) Human Rights	Gender Inequality	0.1	35	3.5
	Human Health Issues	0.1	90	9
(External) Community Infrastructure	Drinking Water	0.1	53.49	5.349
	Sanitation	0.1	80.22	8.022
Global Social Index		68.032		

3.2.4.2 Global Governance Index (GGI)

The GGI of China was calculated as the average of its five components scores, which were converted directly from WGI database as shown in Table 11.

Table 11 China Global Governance Index Breakdown

GGI of China	Single Score	Weight	Weighted Score
Political Stability (PV)	73.0	20%	14.60
Governance Effectiveness (GE)	45.9	20%	9.18
Regulatory Quality (RQ)	57.4	20%	11.48
Rule of Law (RL)	60.2	20%	12.04
Control of Corruption (CC)	53.1	20%	10.62
Global Governance Index	57.91		

By averaging the GSI and GGI of China, the SR Score of China was obtained.

3.2.4.3 Calculate Supply Chain SR Score

Through the same assessment processes of evaluating China's Social Risk, the SR scores of all 23 countries and regions were calculated in the same logic. (Find more details in the Appendix B)

Finally, based on their GSCs indicated by the supply chain mapping, each sector's SR score was calculated as shown in Table 12.

Table 12 Apparel Industry Social Risks Score Conversion

Sector	Index	Index Score	SR Score
Raw Material Production	Global Social Index	48.36	43.17
	Global Governance Index	37.97	
Fiber Production	Global Social Index	64.7	59.12
	Global Governance Index	53.54	
Spinning	Global Social Index	66.26	60.86
	Global Governance Index	55.46	
Weaving	Global Social Index	66	60.62
	Global Governance Index	55.23	
Dyeing	Global Social Index	55.53	49.31
	Global Governance Index	42.83	
Tailoring	Global Social Index	70.54	63.91
	Global Governance Index	57.29	

From Figure 4, the trends of GSI and GGI among all supply chain sectors were found synchronous, indicating that social impact usually reacts with governance impact. What's more, among the six sectors, tailoring SR was the highest one, while raw material production SR was the lowest one.

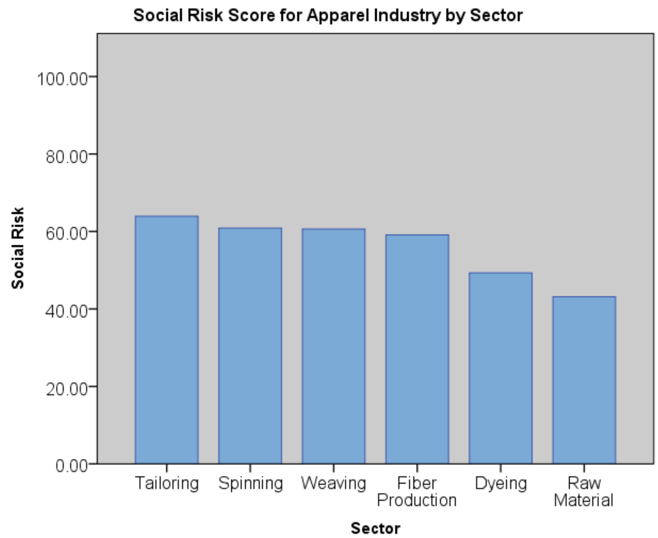

Figure 4 Social Risk Score for Apparel Industry by Sector

As shown in Figure 5, two OECD countries, South Korea and USA, could be found with SR scores lower than 35. According to the result of supply chain mapping, the combination of the GSC of these two main players was 26.33%, contributing more than a quarter of total global raw material supply. However, we could find in Figure 6 that all the main players had SR scores higher than 50. Therefore, tailoring sector had highest social risk in the global apparel supply chain.

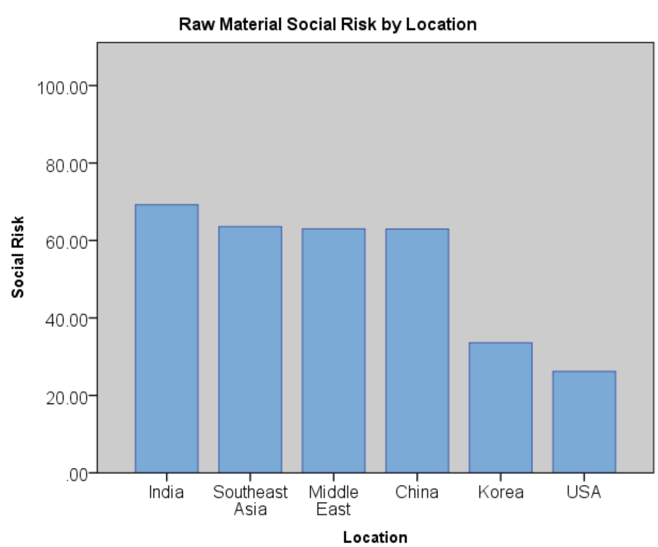

Figure 5 Raw Material Social Risk Score by Location

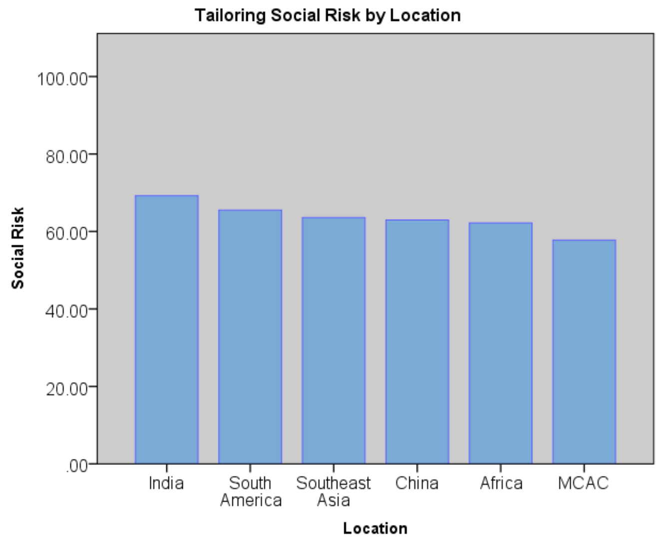

Figure 6 Tailoring Social Risk Score by Location

3.2.5 Supply Chain Analysis

To analyze the apparel supply chain sustainability, the above risk assessment results were further applied to risk assessment space (RAS) analysis and materiality analysis, which were two risk prioritization methods in this study. Followed by the risk prioritization, several risk mitigation strategies based on industry level were developed for the apparel industry.

3.2.5.1 RAS Analysis

The visualization of supply chain sustainability risk assessments is shown in Figure 7. In this three-dimension demonstration, each axis represents the percentile normalization of operation, environmental, and social risks of each sector. The normalized systematic supply chain sustainability risk was calculated based on Equation 3-3, where s represents a whole sector (raw material, etc), t represents each dimension (operational, environmental, social), and i represents specific dimension in each of the sector. The six spots shows ranking of supply chain sustainability risks for each of the six sectors: the longer the distance of the spot to the origin, the higher the overall normalized risk is. As a result, dyeing sector with the highest environmental and operational risk was ranked the first in terms of overall supply chain sustainability risks, followed by fiber production, weaving, spinning, tailoring, and raw material production. As indicated before, the upstream suppliers to the apparel industries tend to be small private companies which are hard to track. As dyeing is the tier 2 supplier to the consumer brands in the supply chain, the barrier to mitigate environmental and operational risks in the dyeing processes would be even stronger. As a result, a strategic suggestion for the industry to improve sustainability along its supply chain could be to focus on improving transparency and supplier engagement. For example, establishing industrial organizations and associations aiming to increase supply chain visibility could be one of potential approaches.

$$Normalized\ SCS\ Risk_t = \sqrt{\sum_{t=1,i=1}^{t=3,i=6}\{[s_{i,t} - \min(s_t)]/[\max(s_t) - \min(s_t)]\}^2} \qquad (3\text{-}3)$$

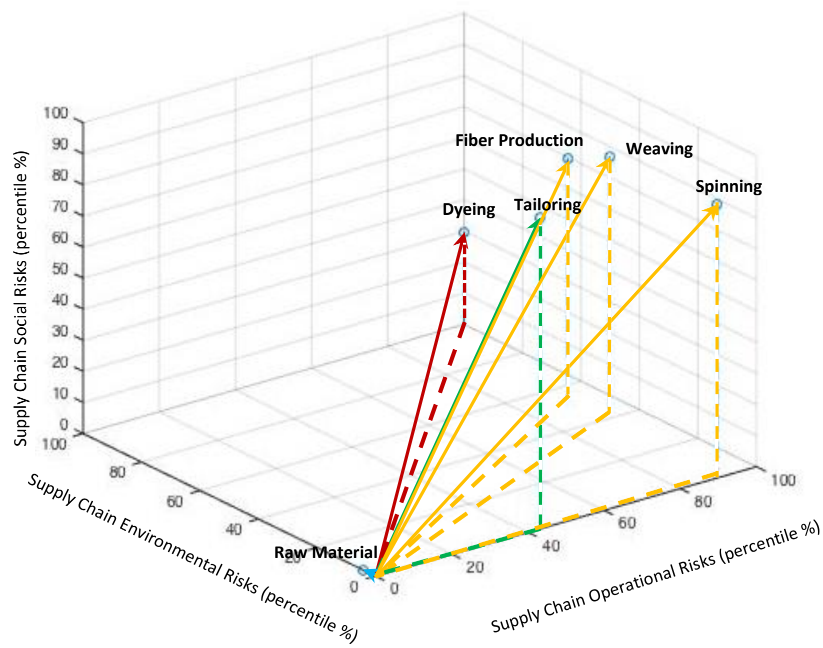

Figure 7 Apparel Industry Risk Assessment Space

3.2.5.2 Materiality Analysis

For practical supply chain design and management, supplier's location and its manufacturing activity are the two main factors of decision-making. The potential risk relevant to supplier's location is defined as Location-Based Risk (LBR), and the potential risk relevant to supplier's manufacturing activity is defined as Activity-Based Risk (ABR) in this study. In order to further apply the above risk assessment to the decision-making of supply chain management, the operational risk, environmental risk and social risk are classified into LBR and ABR; then the materiality analysis of LBR and ABR is conducted to prioritize the sustainability risk of different sectors along a supply chain.

In the case study of apparel industry, the similar materiality analysis for its supply chain sustainability risk was conducted. Firstly, every single risk in each of triple bottom lines was analyzed again and classified into the LBR and ABR. Then every single LBR and single ABR extracted from OR, ER, and SR of one sector were added up separately as the total LBR score and total ABR score of the sector. In this case, because of the limited data resources, the original data of SR was only relevant to suppliers' location, while the original data of OR and ER was only related to suppliers' manufacturing activities. Therefore, all LBRs came from SR, and all ABRs came from OR and ER.

After obtaining the total LBR score and total ABR score of every sector in apparel industry, the scores of six sectors were normalized through percentile ranking, which was similar to the normalization in the above risk assessment space analysis. Finally, six sectors were plotted in the four quadrants of the following two-dimensional diagram to reveal the relative materiality of the risk of each sector.

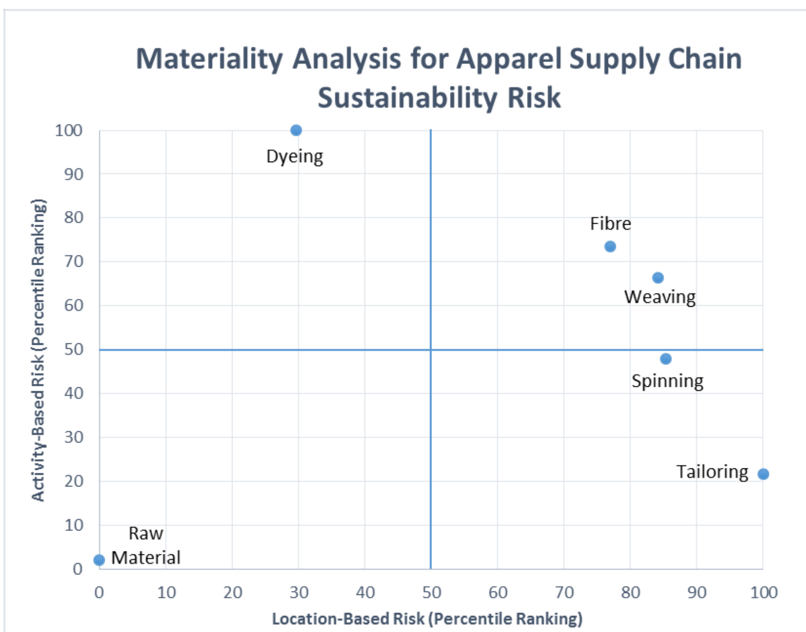

Figure 8 Materiality Analysis for Apparel SCS Risk

According to Figure 8, the sectors of fiber production and weaving have both of relatively high LBR and ABR; the sectors of tailoring and spinning have relatively high LBR; the main risk in dyeing sector is ABR; the sector of raw material production has relatively low LBR and ABR.

Although dyeing sector was indicated as the sector with highest sustainability risk in the risk assessment space analysis, this materiality analysis revealed that the sectors of fiber production and weaving should be prioritized, as they have both of high LBR and high ABR. As for dyeing sector, the risk mitigation strategies should mainly focus on suppliers' manufacturing processes improvement, while relocating suppliers in new locations with lower risk should be the main consideration to reduce sustainability risk in spinning sector and tailoring sector.

3.3 Case Study of Automotive Industry

In the case study of automotive industry, the first step was to conduct supply chain mapping, followed by sustainability risk assessment and analysis.

3.3.1 Supply Chain Mapping

In global automotive supply chain analysis, six sectors were selected to form the simplified supply chain, which were engine, body shell, transmission, tire, electric system and assembly, based on several industry reports and academic literature related to automotive supply chain sustainability (e.g. ARPAC[26], Steve Hung et al[27]).

When mapping the global automotive supply chain, determining the global supply concentration (GSC) was still the main part of the supply chain study, due to its essential role of helping to understand the global supply chain structure and assess the associated risk. Among the six sectors, the GSCs in sectors of engine, body shell, transmission, electric system and assembly were determined based on the relevant data of 2013 in MarkLines Automotive Industry Database[28]. The GSC in tire sector were determined based on the data of 2006 tire production by country in RubberNews.com.[29]

[26] Association of Auto Part Recyclers (ARPAC). Environmental and Socioeconomic Assessment of the Quebec Automotive Parts Recycling Sector. Nov. 27, 2013.
[27] Steve Hung, Aleksandar Subic, Joerg Wellnitz. Sustainable Automotive Technologies 2011. New York: Springer. 2011.
[28] MarkLines Automotive Industry Database. www.marklines.com
[29] Tire Production by Country. RubberNews.com. http://www.rubbernews.com/article/TB/20090201/STATISTICS/121019919/tire-production-by-country. Feb. 1, 2009.

In the MarkLines Database, there was specific annual data of engine production and car production, while there was only specific information of global top 500 suppliers for all automotive systems. Therefore, in this case study, the share of each producing country or region in engine production and car production was assumed as its GSC in sectors of engine and assembly. Because most of body and shell was produced by automakers and in their own assembly factories or the nearby factories, the GSCs in the sector of body shell were assumed to be the same as assembly sector. The share of each supplier country or region in global top 500 suppliers for transmission and electric system was assumed as its GSC in sectors of transmission and electric system, as there was no specific transmission production data, and the global production data of electric system parts was impossible to collect. Figure 9 shows the main results of global automotive supply chain mapping. (Find more details in Appendix C.)

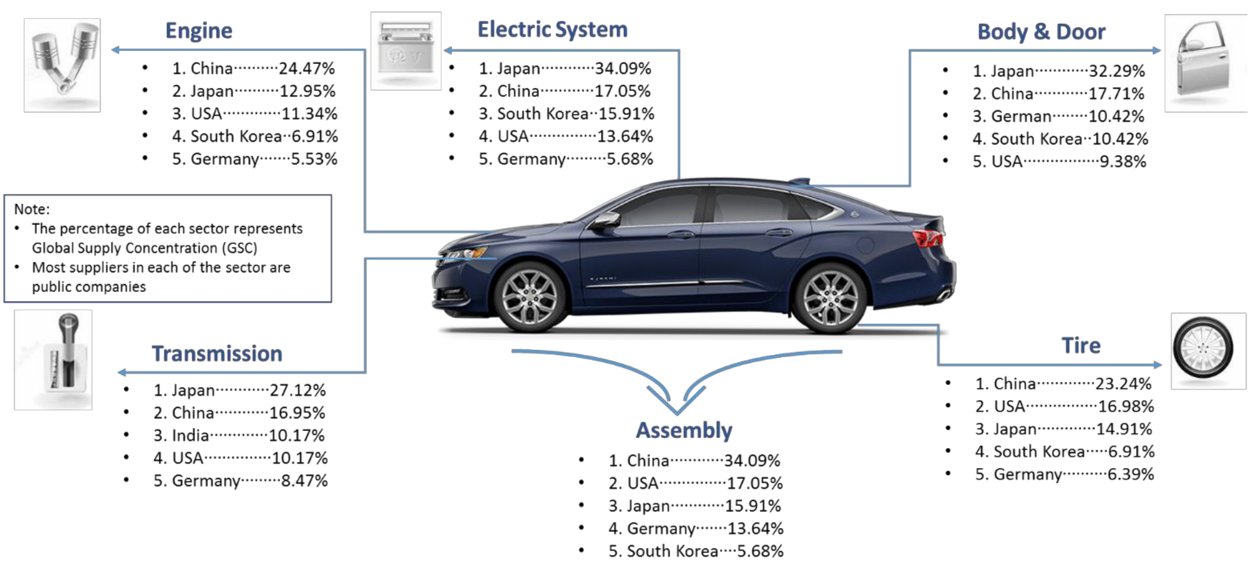

Figure 9 Automotive Industry Supply Chain Mapping

3.3.2 Operational Risk Assessment

The operational risk of automotive industry's supply chain is listed in Table 13. As shown in Table 13, engine had the highest operational risk score among all of the sectors, while electric system had the lowest.

Table 13 Automotive Industry Supply Chain Operational Risk Score by Sector

Sector	Operational Risk Score
Engine	37.96
Door & Body	24.67
Transmission	31.88
Tire	33.88
Electric System	15.17
Assembly	24.67

Table 14 Automotive Industry Supply Chain Operation Risk Score Breakdown by Sector

Sector	Supply Risks	Process Risks	Demand Risks	Corporate-level Risks
Engine	3.00	3.25	4.33	4.60
Door & Body	3.33	0.00	2.33	4.20
Transmission	3.33	1.75	2.67	5.00
Tire	1.67	0.00	1.00	3.40
Electric System	3.33	3.75	2.67	3.80
Assembly	3.33	0.00	2.33	4.20

**Note: The door & body and assembly shares the same operational risks in our model.*

As shown in Table 14, digging deeper into the detail, we could find out that the reason why engine has the highest operational risks comes from its highest demand risks and corporate-level risks and its second highest process risks. If we further break down the factors, we could find out that engine has very high risks in change in consumer preference. To be specific, consumers are probably to switch their preference in automotive industry. For example, PHEV, EV and fuel cell cars are major challenges for traditional automotive industry. Additionally, engine has very high intellectual property risks since engine manufacturing is expanding globally, especially to developing countries (China, India). Thus, intellectual properties, or specifically technologies and patents, may be at risk due to lack of comprehensive legislation.

3.3.3 Environmental Risk Assessment

3.3.3.1 System Boundary

Similar to the apparel industry, cradle to gate life cycle analysis was applied to assess the environmental impact and environmental risk of the automotive supply chain.

Based on the supply chain mapping and supply chain structures, the "Average Product" for the automotive industry included engine, drivetrain, electronic system, tire, body & door, and assembly of the auto.

3.3.3.2 Functional Unit

As mentioned before, the study prioritized 6 components and processes in the "Average Product", which is a simplified model due to time and resource limitation. The "Average Product" here was not a single vehicle from any automaker, but a representative of normal industrial material and manufacturing processes.

3.3.3.3 Cradle to gate Inventory

Based on publicly available data, the cradle to gate inventory of the key components is listed in Table 15.

Based on the current corporate social responsibility reports in automotive industry, the study assumed that the main input for auto assembly was mainly water and electricity.

Similar to apparel supply chain, the electricity (kWh/vehicle) intensity and water intensity (kg water/vehicle) was estimated (See Appendix C). The average water intensity was 4000 kg/vehicle[16].

Table 15 Life cycle Inventory of Key Components in Automotive Industry

Component	Subcomponent	Material	Weight (kg)	Manufacturing Process
Engine[30, 31, 32]	Crankshaft[33]	Cast iron	20	Heating, casting, surface treatment
	Engine Block	Aluminum alloys	54.4	Sand casting, surface treatment
	Others	Aluminum alloys	18.6	Sand casting, surface treatment
Drivetrain[34]	Cases	Aluminum Alloy	30	Casting, machining
	Oil Pan	Aluminum	3	Casting, machining
	Torque Converter	Steel	15	machining, welding
	Valve Body	Cast Iron	8	sand casting
Tire[35]	Rubber	Polybutadiene	6.3	
	Steel Cord	Steel	1	
	Bead Wire	Yarn	0.3	
	Rayon cord	PX	0.4	
Body & door[36]	N/A	Steel	415	Blast furnace, rolling, welding, machining
		Aluminum alloys	250	Sand casting, surface treatment
		Magnesium alloys	7.9	
Electric system[37]	Cords	Copper	386	
	Plastics	Glass fiber	322	
	Metals	Steel	20.5	
		Aluminum	7.69	

[30] "Engine Block Manufacturing Process." *Mechanical Engineering*. Web. 9 Apr. 2015. <http://newengineeringpractice.blogspot.com/2011/08/engine-block-manufacturing-process.html>.
[31] Nguyen, Hieu. "Manufacturing Processes and Engineering Materials Used in Automotive Engine Blocks." *School of Engineering Grand Valley State University*. 8 Apr. 2005.
[32] Das, Sujit. "Life Cycle Modeling of Propulsion Materials." *Oak Ridge National Laboratory*. 11 May 2011
[33] Kane, Jack. "Crankshaft Design, Materials, Loads and Manufacturing." *EPI Inc.* Web. 24 Jan. 2015. <http://www.epieng.com/piston_engine_technology/crankshaft_design_issues.htm>.
[34] "BMW Automatic Transmission E46 Guide." *BWM*. Web. 20 Mar. 2015. <http://www.bmwtech.ru/pdf/e46/ST034/12 Automatic Transmission Internet.pdf>.
[35] Ferrer, Geraldo. "The Economics of Tire Remanufacturing." *Resources, Conservation and Recycling* 19.4 (1997): 221-55. Science Direct. Web. 9 Apr. 2015.
[36] "Bodyshell Concept: Effective Lightweight Construction with an Intelligent Material Mix." *Daimler Global Media*. Web. 9 Apr. 2015. <http://media.daimler.com/dcmedia/0-921-1417474-1-1422654-1-0-0-0-0-0-11702-0-0-1-0-0-0-0-0.html>
[37] Dose, Julia, and André Greif. "LCA-studies of Electrical and Electronic Components in the Automotive Sector." *Institute for Environmental Engineering, Department of Systems Environmental Engineering*. Web. 31 Jan. 2007. <http://www.netzwerk-lebenszyklusdaten.de/cms/webdav/site/lca/shared/Veranstaltungen/2005LcaWerkstatt/ArbeitsgruppeA/A1_Dose.pdf> .

3.3.3.4 Environmental impact and ER Score

With a similar methodology as apparel supply chain, the ER score of the sectors across automotive supply chain is listed in Table 16.

Table 16 LCIA and ER Score of Automotive Supply Chain

Sector	Weighted ReCiPe Score	ER Score	Score Breakdown	
Engine	532.72	100.00	Human Health	84.09
			Ecosystem Quality	5.88
			Resources Depletion	10.03
Door & Body	218.98	41.11	Human Health	19.26
			Ecosystem Quality	10.24
			Resources Depletion	11.60
Drivetrain	37.66	7.07	Human Health	3.15
			Ecosystem Quality	1.39
			Resources Depletion	2.53
Tire	17.46	3.28	Human Health	1.07
			Ecosystem Quality	0.74
			Resources Depletion	1.47
Electronics System	219.18	41.14	Human Health	14.98
			Ecosystem Quality	7.02
			Resources Depletion	19.14
Auto Assembly	61.86	11.61	Human Health	4.37
			Ecosystem Quality	2.57
			Resources Depletion	4.67

As it is illustrated here, engine, electric system, and door & body manufacturing are the top three sectors with environmental risks in automotive industry. For the engine sector, aluminum-based engine components such as blocks, cylinders, and crankshafts contribute about 43% of the overall risks. To better achieve their fuel-economy goals, auto light-weighting substituting aluminum with steel in engine and body shells is a current trend in the industry. However, as aluminum is has a much significance energy intensity (MJ energy / kg metal) than steel in the material manufacturing process, environmental risk may shift from use phase to upstream supply chains in automotive industry (more details in Appendix B).

3.3.4 Social Risk Assessment

In this part, the whole assessment process of each country or region was completely the same as the process in the case study of apparel industry. Therefore, specific calculation was not presented here, but the detailed results of all 45 countries and regions along the global automotive supply chain could be found in the Appendix C.

Finally, according to their GSCs indicated by the supply chain mapping, each sector SR score of supply chain is calculated as shown in Table 17.

Table 17 Apparel Industry Social Risk Conversion

Sector	Index	Index Score	SR Score
Engine	Global Social Index	46.97	33.79
	Global Governance Index	20.6	
Body Shell	Global Social Index	38.76	31.24
	Global Governance Index	23.73	
Drivetrain	Global Social Index	43.44	36.07
	Global Governance Index	28.69	
Tire	Global Social Index	46.36	40.18
	Global Governance Index	34	
Electric System	Global Social Index	40.16	32.56
	Global Governance Index	24.96	
Assembly	Global Social Index	48.2	42.41
	Global Governance Index	36.62	

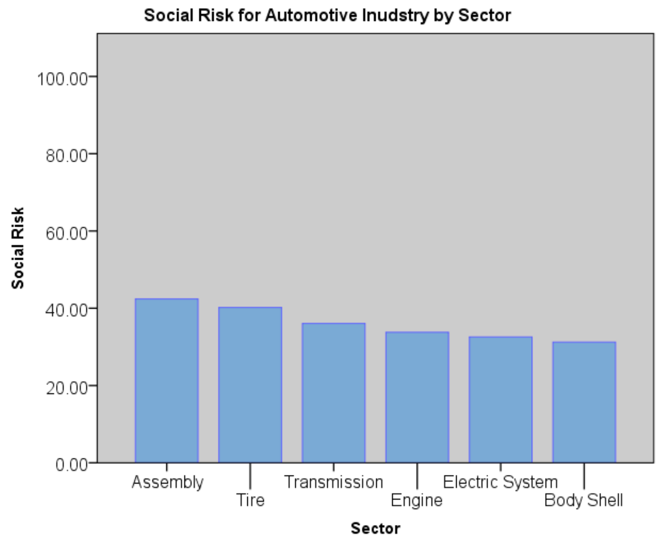

Figure 10 Social Risk Score for Automotive Industry by Sector

From Figure 10, the sectors with the highest SR is assembly and body shell, while the one with the lowest SR is electric system. As the assumption of body shell sector indicated in the supply chain mapping, the following analysis related to assembly sector could also represent the analysis of body shell sector.

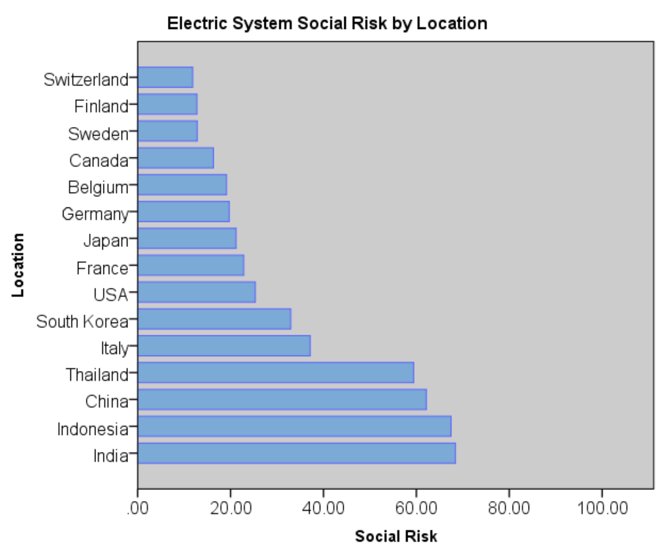

Figure 11 Electric System Social Risk Score by Location

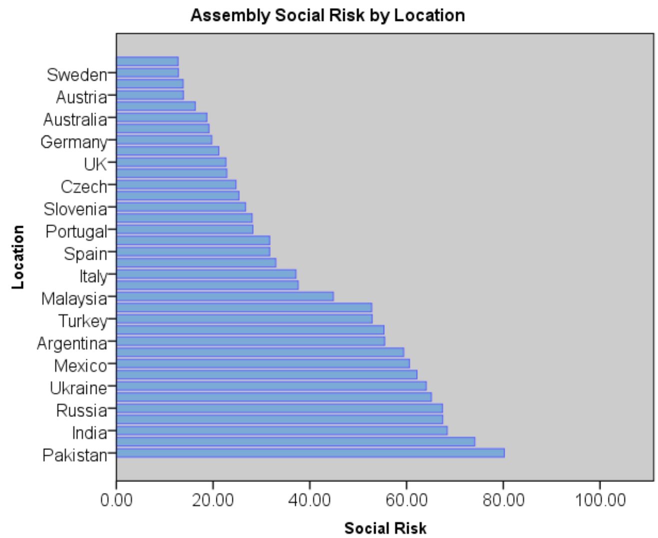

Figure 12 Assembly Social Risk Score by Location

Figure 11 shows that although the four non-OECD countries have high SR score above or almost 60, they supply only 21.59%, around one-fifth of total amounts of electric system parts in the world. Almost four-fifths of the worldwide supply of electric system comes from OECD countries with much lower SR scores. However, Figure 12 shows that almost half of vehicles around the world are produced by non-OECD countries with SR scores lower than 50. Therefore, assembly sector had highest social risk in the global automotive supply chain.

3.3.5 Supply Chain Analysis

To analyze the automotive supply chain sustainability, the above risk assessment results were further applied to risk assessment space analysis and materiality analysis, which were two risk prioritization methods in this study. Followed by the risk prioritization, several risk mitigation strategies based on industry level were developed for the automotive industry.

3.3.5.1 Risk Assessment Space Analysis

With similar visualization and normalization logic to apparel supply chain, Figure 13 indicates that engine sector has the highest systematic supply chain sustainability risk, followed by auto assembly, transmission, electric system, tire, and body & door.

Due to the nature that most of these suppliers are public large companies, one effective strategy for automotive industry to upgrade to sustainable supply chain could be to increase industrial standards, supplier codes, and supplier auditing to address issues for the suppliers.

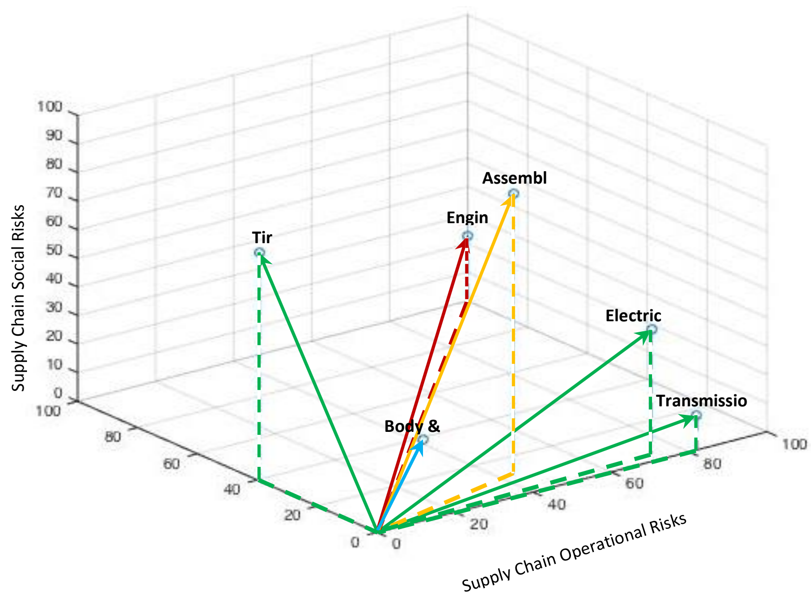

Figure 13 Automotive Industry Risk Assessment Space

In the case study of automotive industry, the similar materiality analysis as in the case study of apparel industry was conducted for automotive supply chain sustainability risk. The result is shown in Figure 14.

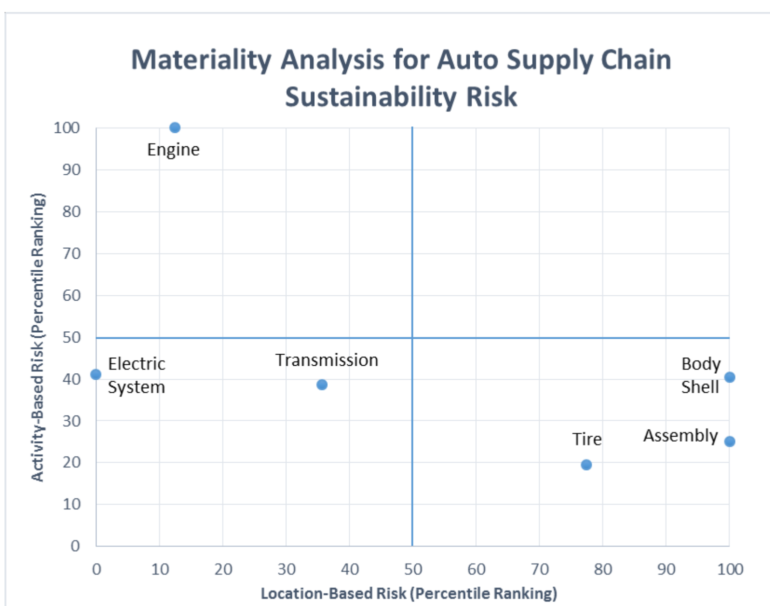

Figure 14 Materiality Analysis for Automotive SCS Risk

According to Figure 14, no sector have relatively high LBR and ABR simultaneously; the sectors of body shell, assembly and tire have relatively high LBR; the main risk in engine sector is ABR; transmission sector has both of relatively medium LBR and ABR; the sector of electric system has relatively low LBR and medium ABR.

For engine sector, the risk mitigation strategies should be to focus on suppliers' manufacturing processes improvement. However, as for the sectors of body shell, assembly, and tire, although the above analysis indicated that they all have relatively high LBR, it is difficult and infeasible to relocate these sectors in new locations with lower risk to mitigate sustainability risk. This is mainly because current and future trend of automotive industry is the localization of vehicle assembly so that the manufacturing is closed to the market. Fast-growing markets in many emerging countries and regions due to their increasing demand of private vehicle further enhance the trend. Therefore, more and more assembly plants are built in these emerging markets with high LBR, and this is also the reason why the sectors of body shell and assembly are high-LBR. As for tire, different from engine and transmission requiring high technology, it is also produced closed to the market. Thus, this sector also has high LBR, but it is infeasible to be relocated.

IMPLICATIONS AND DISCUSSIONS

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4 IMPLICATIONS AND DISCUSSIONS

4.1 Supply Chain Comparison

In the previous section, the study applied the supply chain sustainability evaluation method onto two selected supply chains: “deep structure” and “broad structure” supply chains represented by apparel and auto industry, respectively. In the meantime, different strategic suggestions were provided to prioritize the industries’ resources to upgrade for supply chain sustainability due to their distinctions in supply chain type and key players in the sectors. In this section, we would like to discuss where the variations came from, and why different strategies were concluded.

As we discussed in the supply chain mapping, variation of the two main supply chain structures came from the nature of the goods in its industries. Apparel industry has a deep structure supply chain because the product itself is relative simple. The success of each of the sector along the supply chain relies on the completeness of the sectors before them. Because the entry barriers for each of the sectors are low, most of the players are small scale companies (See Appendix B). On the contrary, the automotive industry has a broad structure supply chain because of its multi-component attribute. Each of the components has high technical requirements and high entry barrier, so large scale or public companies are common in the supply chain. Also, most of the components can be produced separately without relying on the completeness of other ones. Here, we can conclude that the source of distinction in supply chain structure came from the industrial motivation to maximize internal resource allocation efficiency: the more complex the product is, the supply chain incline to be more “broader”; the simpler the product is, the supply chain incline to be more “deeper”. Hybrid supply chain structure may exist if the product of the industry is moderate complex. As a result, structural complexity of the product in the industry reflects to its supply chain structure, while entry barrier of each of the sectors determines the scale of its players.

These distinctions in supply chain structure and scales of players are the two key drivers for different strategic suggestions in apparel and automotive industries. In apparel industry, though the consumer brands would like to prioritize their resources to address environmental and operational risks in dyeing mills, it is hard for them to track to this tire of indirect supplier, because most of their direct supplier (the tailoring mills) are small scale private companies with low supply chain standards. This means that unless touch down base on their balance sheets, damaging environmental and social perspectives are purely externalities to those small upper stream companies. Hence, utilizing purchasing power from the consumer brands to improve industrial compliance standards and third party enforcements are possible ways to internalize environmental and social dimension to the risks of their upstream suppliers. To the automotive industry, the public upstream suppliers make the tracking process relatively easier, but due to the complexities of the product itself which composed of thousands of components, it is hard to prioritize industrial resources to address sustainability issues. Therefore, engaging with their first tier direct suppliers (such as engine) and addressing supplier codes and auditing with may be the key strategies for the automotive industry to upgrade to improved supply chain sustainability.

4.2 Generalization

Other than the selected case study of automotive and apparel industry, this methodology could be applied to other industries as well, following the steps of:

1. Supply chain mapping: categorize your supply chain into deep structure, broad structure, or mixed structure based on the product in your industry. Define each sector across the supply chain, and establish supplier list (key players) in each of the sector.
2. "Triple Bottom Line" assessment. The systematic risk quantifying method could be applied to most of the entity industries with multiple supply chains.
3. Strategic suggestions. Based on the hotspots identified in the "Triple Bottom Line" assessment and your supply chain mapping, provide strategic analysis of the issue and feasible suggestions to prioritize your strategy.

For example, with similar feature to apparel industry, food and consumer goods industries could follow the methodology to find out sustainability hotspots on their upper stream supplier (tier 2 an up). In the same way, similar to automotive industry, consumer electronic and construction machine industries could utilize the method to prioritize which direct supplier to engage with first. It is worth mentioning that even within the same industry, supply chain structure could vary, analysts should remain flexible to categorize supply chain types and key players for a specific study, and provide best suitable strategic suggestions.

4.3 From Industry to Corporate

One of the characteristics of our model is that it primarily focused on industry-level activities rather than corporate-level operations. One of the reasons is that we could only get access to publicly available data at this stage. Another reason is that our purpose of this study was to present a methodology as demonstration rather than solving a specific corporate problem. Also, the supply chain sustainability upgrading strategies that we provided were intended to provide insights to international organizations and industrial associations.

However, customizing our model for corporate-level usage is still a promising effort, given that more and more companies emphasize on supply chain sustainability issues. To make sure that the model could function well in corporate environment, we would like to provide some suggestions on customization:

- **Companies might have different prioritizations.** Our model assumed that Operational Risk, Environmental Risk and Social Risk are of the same importance in supply chain sustainability risk assessment. However, in real-world business, some companies might have other prioritization on different aspects. For example, some companies might care a lot about environmental issues since they think environmental risk is a key risk for their business. As a result, they would assign a much higher weight to environmental risk. In that case, our model must be customized based on their preference on the "Triple Bottom Line".
- **Companies might use more specific data and indicators.** As we mentioned before, our data were all from publicly available sources and our model was evaluating the average status of the industry. Additionally, we used a lot of simplifications and assumptions. When companies are using the model, they may probably want to change some of the indicators and data based on their own judgment and purpose.

- **Companies might have different strategies.** The supply chain sustainability risk-neutral strategies that we provided are based on our data sources and assumptions. Also, they were from the perspective of international organizations and industrial associations. Thus, to achieve the best effect, companies should incorporate and customize the supply chain sustainability strategies into their overall corporate strategy including growth strategy, financial strategy, operational strategy, etc.

4.4 Potential Improvement Opportunities

Our model has several potential improvement opportunities:

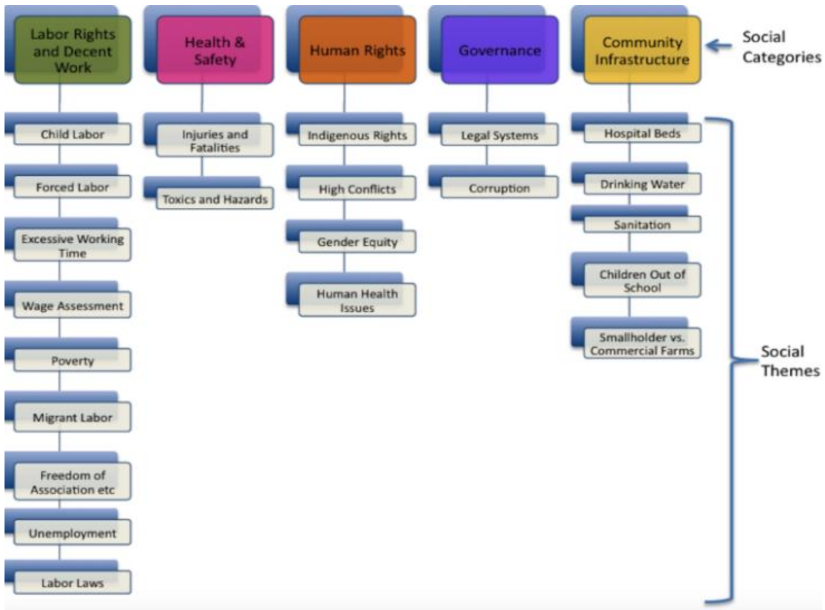
Data availability & accuracy. Our model made several simplifications and assumptions. Part of the reason was that we lacked proper data. As the data availability and accuracy is better, the assessment results and implications from our model would be better. In this sense, we might look for some partnership with some international organizations and industrial organizations who could provide high-quality and large scale data.

Transportation & time horizon. In the analysis of our model, we omitted the impact of transportation and time horizon due to the budget and time commitment of the project. In fact, they could actually be very important in terms of supply chain sustainability. Our next step is to incorporate these two factors into our existing model. In this way, a more comprehensive and more convincing model will be presented.

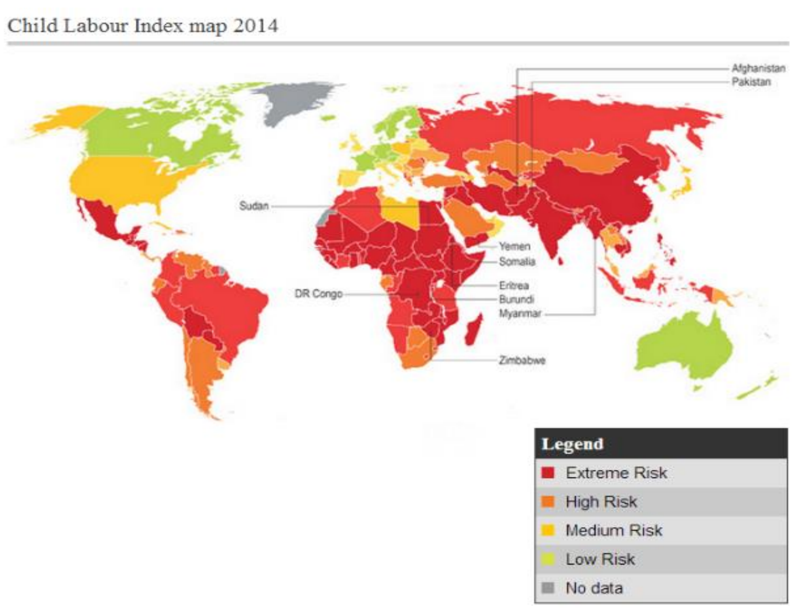
Scope Expansion. As we mentioned before, the scope of our study did not include the usage and the recycling phases due to the budget and time commitment of the project. To better address the supply chain sustainability issue, expanding the scope of study to include these two stages is essential. In this way, our model could be interpreted into more interesting insights and suggestions.

APPENDIX A – SCS Risk Assessment Methodology

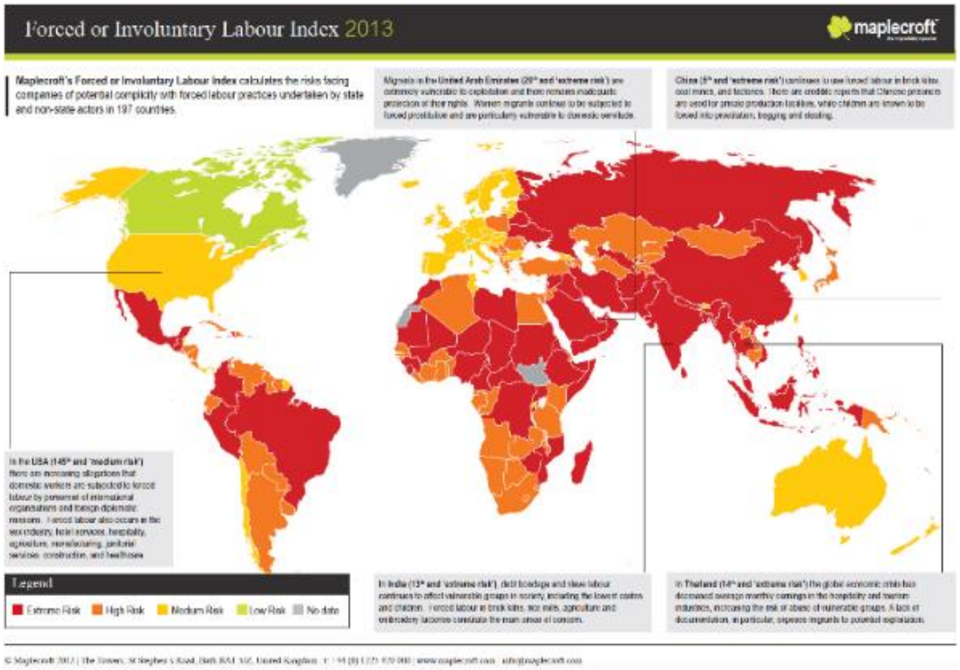
GLOBAL SOCIAL INDEX



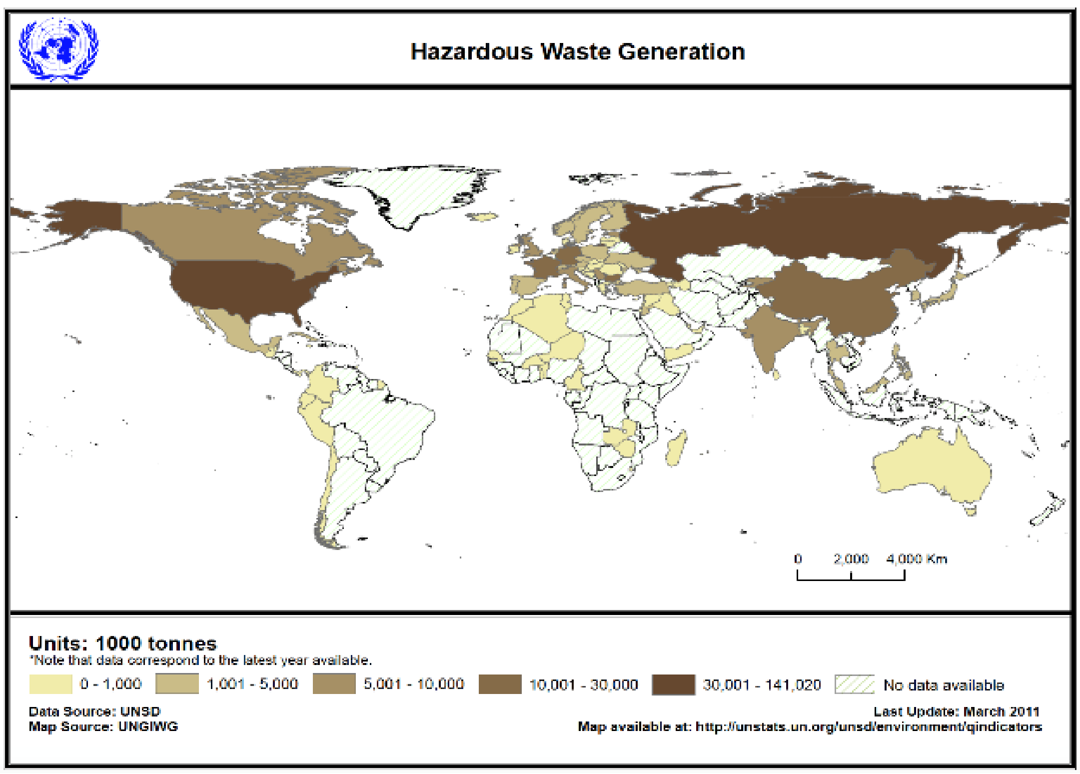
A1 SOCIAL HOTSPOT Social Risk Classification System



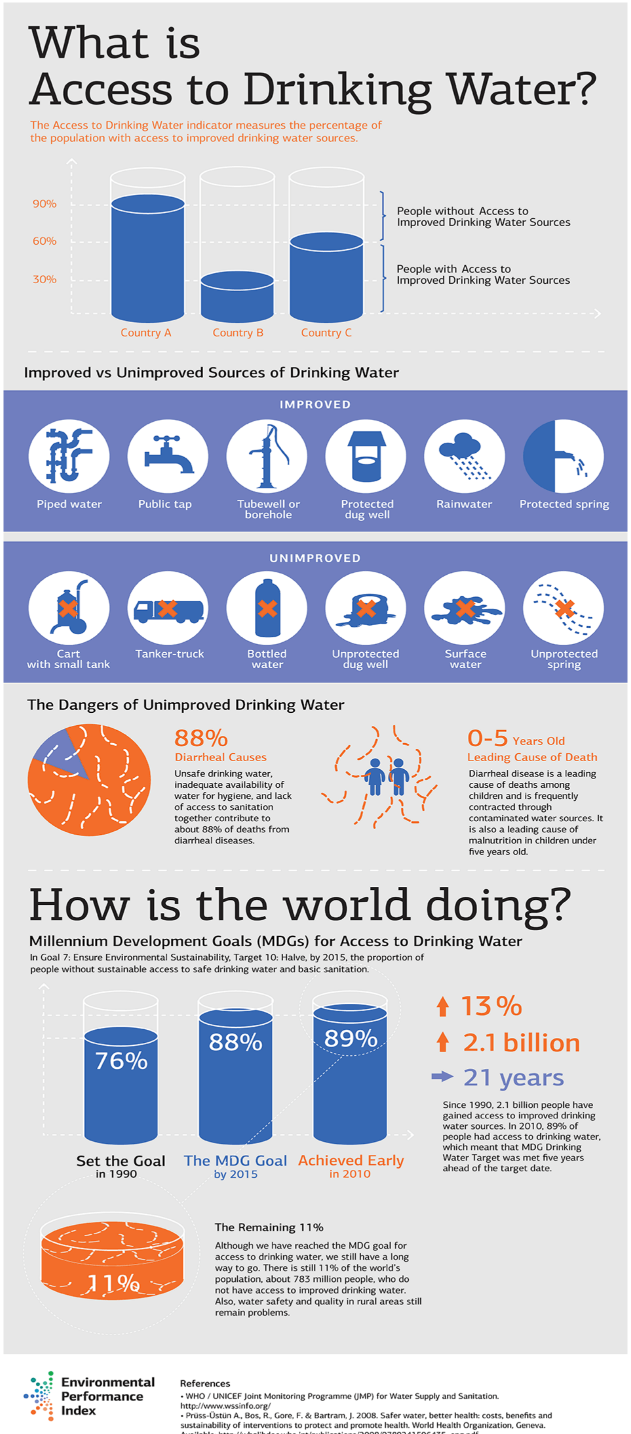
A2 Child Labor Map

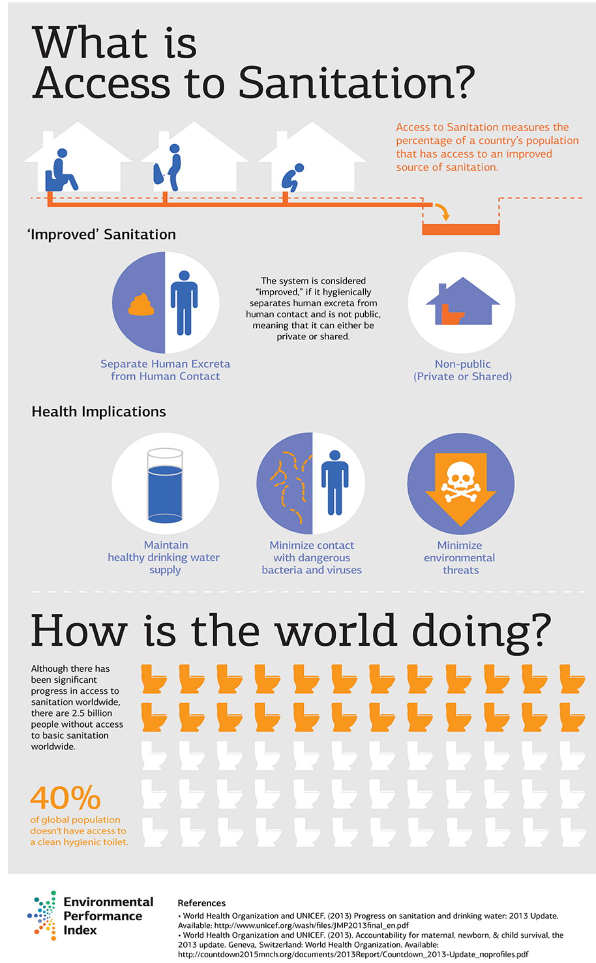


A3 Forced Labor Map



A4 Toxics and Hazards Map





A5 Access to Drinking Water and Sanitation

APPENDIX B – Case Study of Apparel Industry

B1 GLOBAL APPAREL SUPPLY CHAIN MAPPING

B1-1 Raw Material Sector Mapping Results

Raw Material Production	Weighted Average Shares %	Cotton Shares %	PX Shares %
China	22.47%	27.05%	20%
USA	14.63%	13.95%	15%
Korea	11.70%	0.00%	18%
Middle East	10.94%	12.68%	10%
India	14.78%	23.67%	10%
Southeast Asia	6.50%	0.00%	10%

*Note: Raw material production shares% is the weighted average of 35% cotton shares% and 65% PX shares%

B1-2 Fiber Production Sector Mapping

Fiber Production	Production (million metric tons)	Shares %
China	50	76.92%
Northeast Asia	5	7.69%
S & SE Asia	5	7.69%
ME & Africa	1	1.54%
East Europe	1	1.54%
West Europe	1	1.54%
South America	1	1.54%
North America	1	1.54%
Total	65	100.00%

B1-3 Spinning Sector Mapping

Spinning	Production (million spindles)	Shares %
China	110	53.40%
India	50	24.27%
Turkey	12	5.83%
Brazil	10	4.85%
USA	8	3.88%
Italy	6	2.91%
Korea	6	2.91%
Egypt	4	1.94%
Total	206	100.00%

B1-4 Weaving Sector Mapping

Weaving	Production (thousand looms)	Shares %
China	1220	72.19%
Brazil	130	7.69%
India	130	7.69%
Turkey	100	5.92%
USA	50	2.96%
Italy	30	1.78%
Korea	20	1.18%
Egypt	10	0.59%
Total	1690	100.00%

B1-5 Dyeing Sector Mapping

Dyeing	Shares %
China	30%
USA	12%
Rest of Asia	12%
India	10%
South America	10%
Western Europe	10%
Japan	5%
Europe	5%
Mexico	3%
Central America	2%

B1-6 Tailoring Sector Mapping

Tailoring	Shares %
China	40%
India	20%
Southeast Asia	20%
MCAC	10%
South America	5%
Africa	5%

B2 APPAREL ER ASSESSMENT REFERENCE INFORMATION

B2-1 World Electricity Composition by Source

Source of Electricity	kWh / kWh electricity output
Coal	0.29
Natural Gas	0.22
Oil	0.32
Nuclear	0.05
Biomass	0.05
Hydropower	0.04
Solar	0.015
Wind	0.015

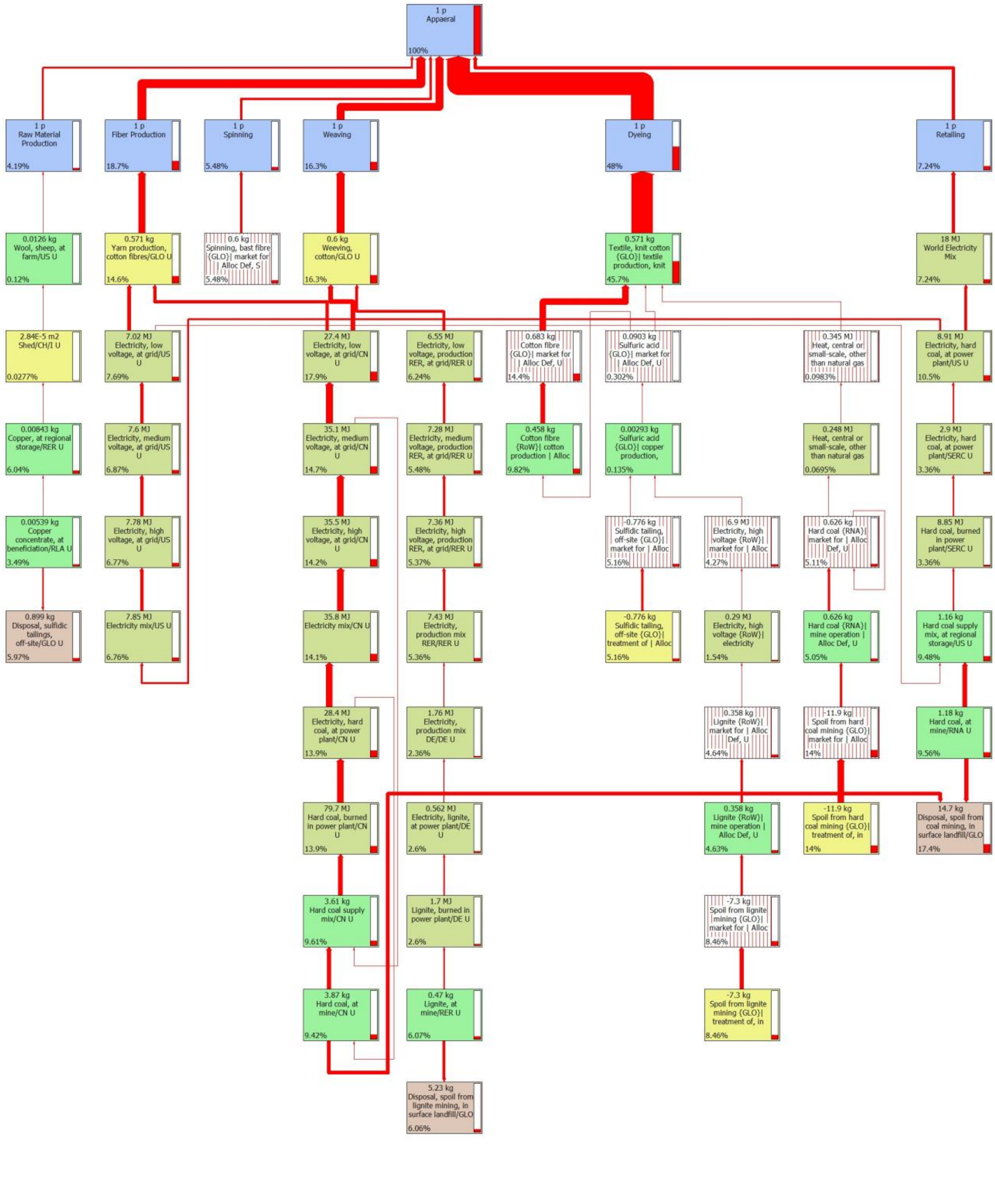
B2-2 Electricity Intensity of Apparel

Electricity Intensity Matrix	Symbol	Value	Unit
World electricity carbon intensity	I_{ele}	668.21	g CO^2/kWh
Apparel industry carbon emission	C_{total}	3.56×10^5	ton
Percentage of tailoring in total carbon emission	P	30%	
Tailoring carbon emission	$C_{tailoring}$	1.07×10^5	ton
Tailoring electricity consumption	$E_{tailoring}$	1.60×10^8	kWh
Apparel industry Annual Sales	$Sales_{Ann}$	2,952	$million
Average price per cloth	P_i	40	$/cloth
Average apparel sales in number	$Sales_{\#}$	7.38×10^7	# cloths
Electricity intensity	E_i	2.17	kWh/cloth

B2-3 Water Intensity of Apparel

Water Intensity Matrix	Symbol	Value	Unit
Average water consumption in apparel industry	W_{app}	88	L/kg Cloth
Average weight per apparel	$Weight_{app}$	0.6	kg
Water intensity	W_i	52.8	L/Cloth

B3 LCA (CRADLE TO GATE) OF APPERAL INDUSTRY



B4 CALCULATION EXAMPLE FOR CHINA'S GSI

In the first part of labor right & decent work, for the Child Labor and Forced Labor components, from the map we could see that the color in China's area are both red indicating that China has an extreme risk in child labor issue and forced labor issue. Thus, China had the score of 100 in these two components. For the Excessive Working Time component, China had an actual working time 46.7 hours per week and the working time limited in China was 40 hours per week. Thus, China had a high actual working time and low working time limited and the score for China was 75 in this component. For the Unemployment component, the unemployment rate for China was 4% and the highest unemployment rate in apparel industry supply chain was 14.49% from Africa, so we calculated it as (4/14.49)*100 and the final score for China in this sector is 28.

In the second part of occupational health & safety, for the Injuries and Fatalities component, the fatality rate in China was 11 per 100,000 workers and the accident rate in China was 8,028 per 100,000 workers. The highest fatality rate and accident rate were both from Egypt that were 24 per 100,000 workers fatality rate and 18,317 per 100000 workers accident rate. Thus, the score for China in this component was (11/24)*50 + (8028/18317)*50, and the final score was 44. For the Toxics and Hazards component, as we could see from the map, the color in China's area was the second dark brown, which means China has 10001- 30000 tons of hazard wastes. So the score for China was 75 in this component.

In the third part of human rights, for the Gender Inequality component, China has the gender inequality index of 0.202, and the highest index in the sector is from Egypt that is 0.58, so the final score for China will be (0.202/0.58)*100 and it is 35 in this component. For Human Health Issue component, China's total health expenditure is 5.4% of GDP. The highest is from USA, which is 17.9% of GDP. The lowest is from India which is 4, so we use [(17.9 – 5.4)/(17.9-4)]*100 and have the final score 90 for China in this component.

In the fourth part of community infrastructure, for Drinking Water and Sanitation components, China already has a score of 46.51 in drinking water issue and 19.78 in sanitation issue; we just use 100-46.51 to have the final score for Drinking Water component which is 53.49 and use 100 – 19.78 to have the final score for Sanitation component which is 80.22.

B5 APPAREL INDUSTRY SUPPLY CHAIN SUSTAINABILITY RISK SCORE

B5-1 Apparel Industry SCS Risk Score before Normalization

Sector/Component	SC Operational Risk	SC Environmental Risk	SC Social Risk
Sector/Component 1: Raw Material	22.71	0.18	43.17
Sector/Component 2: Fiber Production	33.29	0.83	59.12
Sector/Component 3: Spinning	33.29	0.18	60.86
Sector/Component 4: Weaving	33.29	0.65	60.62
Sector/Component 5: Dyeing	34.17	1.42	49.31
Sector/Component 6: Tailoring	27.67	0.13	63.92

B5-2 Apparel Industry SCS Risk Score after Normalization

Sector/Component	SC Operational Risk	SC Environmental Risk	SC Social Risk	Distance to Origin
Sector/Component 1: Raw Material	0.00%	4.05%	0.00%	4%
Sector/Component 2: Fiber Production	92.36%	54.62%	76.89%	132%
Sector/Component 3: Spinning	92.36%	3.47%	85.28%	126%
Sector/Component 4: Weaving	92.36%	40.33%	84.10%	131%
Sector/Component 5: Dyeing	100.00%	100.00%	29.61%	144%
Sector/Component 6: Tailoring	43.27%	0.00%	100.00%	109%

APPENDIX C - Case Study of Automotive Industry

C1 GLOBAL AUTOMOTIVE SUPPLY CHAIN MAPPING

C1-1 Engine Sector Mapping

Engine	Production	Shares %
China	20,691,162	24.47%
Japan	10,953,889	12.95%
USA	9,586,280	11.34%
South Korea	5,841,014	6.91%
Germany	4,680,199	5.53%
Brazil	3,516,416	4.16%
Mexico	3,480,148	4.12%
India	3,445,865	4.07%
France	2,795,611	3.31%
UK	2,549,871	3.02%
Thailand	2,441,053	2.89%
Hungary	2,116,004	2.50%
Spain	1,629,598	1.93%
Austria	1,531,112	1.81%
Poland	1,480,301	1.75%
Canada	1,137,250	1.34%
Indonesia	1,060,956	1.25%
Italy	1,015,302	1.20%
Czech	728,409	0.86%
Russia	682,099	0.81%
Turkey	542,969	0.64%
Slovakia	468,595	0.55%
Iran	412,088	0.49%
Malaysia	364,027	0.43%
Romania	281,611	0.33%
Argentina	252,069	0.30%
Sweden	245,472	0.29%
South Africa	222,976	0.26%
Australia	201,613	0.24%
Uzbekistan	177,471	0.21%
Taiwan	32,181	0.04%
Total	84,563,611	100.00%

C1-2 Transmission Sector Mapping

Transmission	Suppliers#	Shares %
Japan	16	27.12%
China	10	16.95%
India	6	10.17%
USA	6	10.17%
Germany	5	8.47%
South Korea	5	8.47%
Canada	2	3.39%
Italy	2	3.39%
France	1	1.69%
Malaysia	1	1.69%
Mexico	1	1.69%
Norway	1	1.69%
Switzerland	1	1.69%
Thailand	1	1.69%
UK	1	1.69%
Total	59	100.00%

C1-3 Tire Sector Mapping

Tire	Production	Shares %
China	274,230	23.24%
USA	200,281	16.98%
Japan	175,916	14.91%
South Korea	81,508	6.91%
Germany	75,342	6.39%
France	59,000	5.00%
Brazil	42,216	3.58%
Indonesia	41,300	3.50%
Russia	40,417	3.43%
India	32,880	2.79%
Italy	32,017	2.71%
Canada	30,216	2.56%
Poland	28,931	2.45%
Thailand	26,931	2.28%
Turkey	23,905	2.03%
Romania	14,761	1.25%
Total	1,179,851	100.00%

C1-4 Electric System Sector Mapping

Electric System	Suppliers#	Shares
Japan	30	34.09%
China	15	17.05%
South Korea	14	15.91%
USA	12	13.64%
Germany	5	5.68%
India	2	2.27%
Italy	2	2.27%
Belgium	1	1.14%
Canada	1	1.14%
Finland	1	1.14%
France	1	1.14%
Indonesia	1	1.14%
Sweden	1	1.14%
Switzerland	1	1.14%
Thailand	1	1.14%
Total	88	100.00%

C1-5 Assembly (Body Shell) Sector Mapping

Assembly	Production	Shares
China	22,116,825	25.89%
USA	11,066,432	12.95%
Japan	9,553,887	11.18%
Germany	5,736,270	6.71%
South Korea	4,521,429	5.29%
India	3,881,603	4.54%
Brazil	3,450,965	4.04%
Mexico	3,070,134	3.59%
Thailand	2,457,057	2.88%
Canada	2,379,834	2.79%
Russia	2,182,973	2.56%
Spain	1,970,295	2.31%
France	1,737,607	2.03%
UK	1,588,463	1.86%
Indonesia	1,116,961	1.31%
Czech	993,622	1.16%
Turkey	921,058	1.08%

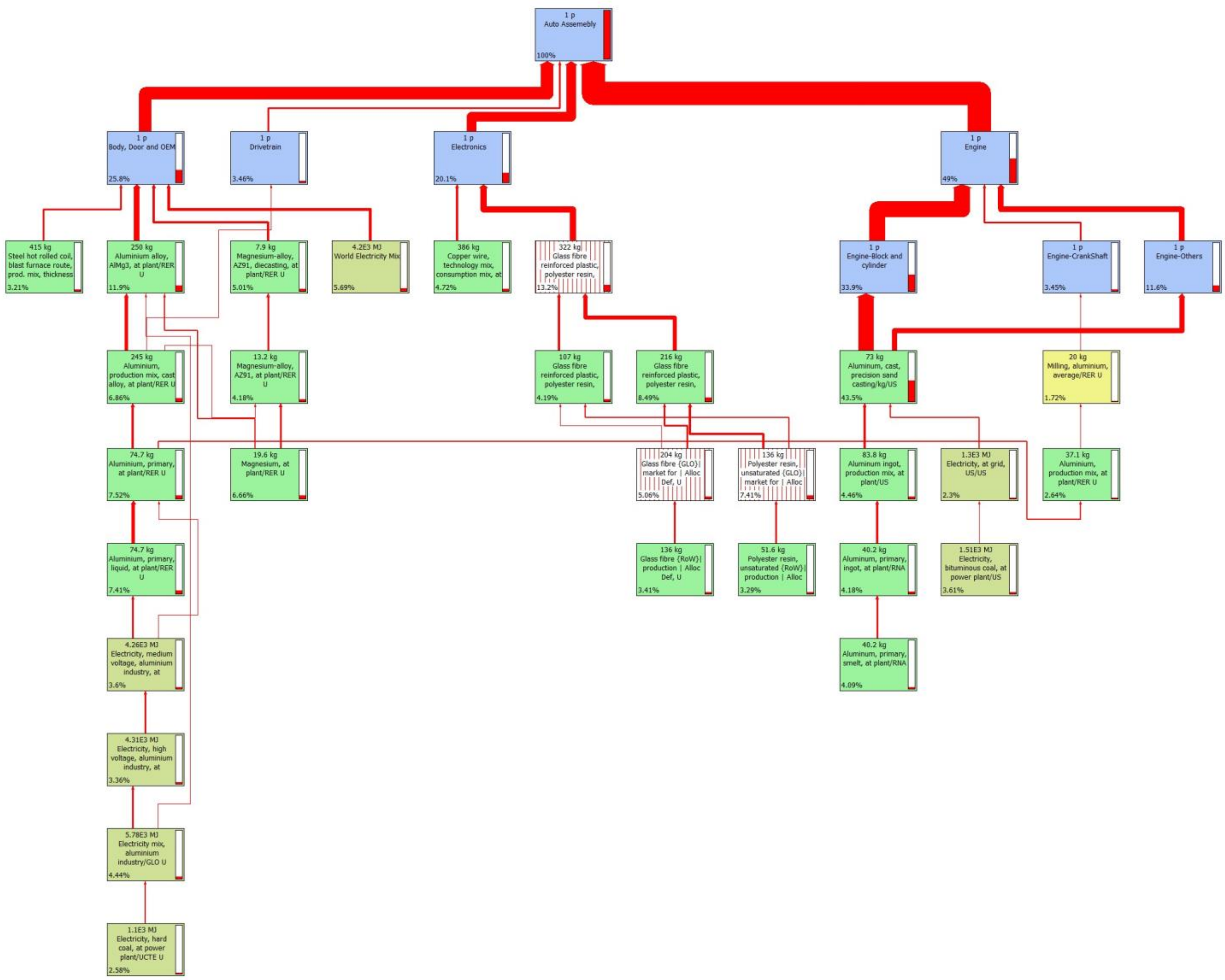
Argentina	791,007	0.93%
Slovakia	757,942	0.89%
Malaysia	601,407	0.70%
Italy	588,415	0.69%
South Africa	555,694	0.65%
Poland	529,061	0.62%
Belgium	483,894	0.57%
Romania	410,997	0.48%
Taiwan	338,720	0.40%
Uzbekistan	246,641	0.29%
Hungary	226,192	0.26%
Australia	215,926	0.25%
Sweden	167,335	0.20%
Portugal	157,829	0.18%
Austria	147,257	0.17%
Pakistan	142,145	0.17%
Slovenia	80,600	0.09%
Venezuela	71,753	0.08%
Philippines	52,260	0.06%
Ukraine	50,467	0.06%
Netherlands	29,183	0.03%
Belarus	22,917	0.03%
Serbia	10,905	0.01%
Finland	3,330	0.00%
Total	85,427,292	100.00%

C2 AUTOMOTIVE ER ASSESSMENT REFERENCE INFORMATION

Table C2-1 Electricity Intensity of Automotive Supply Chain

Electricity Intensity Matrix	Symbol and calculation	Value	Unit
World electricity carbon intensity	I_{ele}	668.21	g CO2/kWh
Auto carbon intensity	C_{auto}	0.78	metric ton/car
Auto electricity intensity	$E_{auto} = C_{auto}/I_{ele}$	1167.29	kwh/car

C3 LCA (CRADLE TO GATE) OF AUTOMOTIVE INDUSTRY



C4 AUTOMITIVE INDUSTRY SUPPLY CHAIN SUSTAINABILITY RISK SCORE

C4-1 Automotive Industry SCS Risk Score before Normalization

Sector/Component	SC Operational Risk	SC Environmental Risk	SC Social Risk
Sector/Component 1: Engine	37.96	532.72	33.79
Sector/Component 2: Body and Door	24.67	218.98	31.24
Sector/Component 3: Transmission	31.88	37.66	36.07
Sector/Component 4: Electric System	33.88	17.46	32.56
Sector/Component 5: Tire	15.17	219.18	40.18
Sector/Component 6: Assembly	24.67	61.86	42.41

C4-2 Automotive Industry SCS Risk Score after Normalization

Sector/Component	SC Operational Risk	SC Environmental Risk	SC Social Risk	Distance to Origin
Sector/Component 1: Engine	100.00%	100.00%	22.83%	143%
Sector/Component 2: Body and Door	41.68%	39.11%	0.00%	57%
Sector/Component 3: Transmission	73.31%	3.92%	43.24%	85%
Sector/Component 4: Electric System	82.08%	0.00%	11.82%	83%
Sector/Component 5: Tire	0.00%	39.15%	80.04%	89%
Sector/Component 6: Assembly	41.68%	8.62%	100.00%	109%

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