

Assessing the social impact of electronics fabrication

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Master's dissertation submitted in order to obtain the degree of Master of Science in Electrical Engineering - Electronic Circuits and Systems

Academic year 2025-2026

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Preface

"Technology is neither good nor bad; nor is it neutral."

– M. Kranzberg

Eight years ago, I learned about semiconductors during my high school physics course – and I was sold. Two years later, I first set foot in the Plateau building Flanders Expo, marking the beginning of my journey in engineering. And now, six years later, I'm finishing up the manuscript that brings an end to my time as an engineering student.

While I have always thoroughly enjoyed learning, my trajectory as an engineering student was not exactly smooth sailing. Though the course contents were interesting, I found it hard to find a purpose for creating electronics in the current state of the world. I asked myself what role electronics plays and where I could have an impact as an engineer.

For several years, these questions remained unanswered. They gnawed at my conscience, and I doubted my decision to pursue this field. While I still do not have a response to these questions, I have decided to make peace with the fact that I alone can not change the world. However, I can try to do my part, and my part, in this case, lies in your hands.

I feel very proud of the work that lies in front of you. Not in the least thanks to the incredible journey writing this thesis has been, I can look back at the past years with pride and appreciation for what I have learned. For that, I am very grateful.

I would like to express my gratitude to my supervisors, Prof. dr. ir. Pieter Bauwens and Dr. ir. Maarten Cauwe. Not only for their excellent supervision, but also for giving me the opportunity to research this topic on my own terms. Thank you for your ever-kind and ever-supportive guidance over the past year.

I am deeply appreciative of the warm and safe learning environment that I have encountered over the past six years. Both as a student and as a student representative, I have encountered many professors and staff who have treated me with kindness, respect, and patience. Thank you for teaching me your ways, extending your honest advice and gentle feedback, and for giving me the space I needed to grow.

Going on an exchange to the University of Padova was an enriching experience on many levels, but most importantly, it was where I found my love for electronics again. *Grazie mille*, to the professors who showed me new perspectives and who met my many questions with riveting enthusiasm. Additionally, I laid the groundwork for this thesis during the course “Microelectronics and Geopolitics”. Together with Silvia Castellucci, I wrote a research paper on the impact of critical minerals tantalum, cobalt and copper on the past and the present of the Democratic Republic of the Congo. I would like to thank Silvia for our enjoyable cooperation, and prof. David Burigana and prof. Alessandro Paccagnella for their guidance during and after the course.

Throughout the past 20 years of my education, I have had the incredible luck to be supported by a village. To begin, my parents, in many shapes and forms: my parents, mama and papa, my stepparents, Lana and Peter, and my grandparents, omi and opi. *Dank je wel, terima kasih, спасибо*. Thank you for being by my side with your advice and comfort, and for supporting me through all of my major projects, from my first New Year's letter when I was 5, up until this very work. To the many other people I consider to be my village, i.e., Astrid and Thomas, my step-siblings, my family, my family-in-law, and my dear friends: thank you for being by my side, and making my life brighter.

Finally, Jarne, thank you for being my biggest supporter and loudest cheerleader. Thank you for encouraging me to pursue this topic, for brainstorming about every doubt I had along the process, for doing the first and the last proofreading of every chapter, and for your honest feedback. On a more personal note; thank you for making sure that my breaks were filled with freshly made latte macchiatos, perfectly peeled oranges, and glasses of water that never ran empty – thank you for sprinkling small moments of magic throughout my life.

Laura Elisabeth Ongmeitan Sondakh

Ghent, May 2026

Ze graaien naar goud, maar wij zoeken naar zilver

– Pommeliers Thijs

Notes

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This master's dissertation is part of an exam. Any comments formulated by the assessment committee during the oral presentation of the master's dissertation are not included in this text.

Laura Sondakh

May 2026

Abstract (Eng.) – Assessing the Social Impact of Electronics Fabrication

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As the electronics industry grows, so does its impact. While the environmental impact has been researched, the social impact has often been overlooked. This work proposes an approach to analyse the social impact of PCBA fabrication. First, the fabrication of passive components, ICs, and PCBs, packaging, and component assembly are considered, and an overview of essential materials is compiled. For each of these materials, social impact is assessed by considering the mining circumstances. The impact is quantified by analysing the following social impact categories: child labour, artisanal and small-scale mining, violent conflict, rule of law, control of corruption, and human development. For each material, the social impact categories are assessed by assigning a score for each of the top 5 producing countries and calculating a weighted average. The result of this work is a comprehensive overview of the social impact of various materials used in electronics fabrication. The materials with the highest social impact are cobalt, tantalum, tin, iridium, ruthenium, rhodium, and chromium. Materials with the lowest social impact are iron, beryllium and lithium. To assess the impact of potential changes within the electronics industry, the share of global production consumed by the electronics industry is assessed for each of the materials. Based on these two analyses, cobalt, tantalum, and silver were selected as three materials of interest for further research. For each of these materials, popular applications and alternative materials are discussed, based on technological properties and cost. These alternatives often pose disadvantages. For some applications, no alternatives exist. Finally, the environmental impact and social impact of a selection of materials are compared. Some materials with a high social impact have a low environmental impact, and vice versa. It becomes clear that there is no 'ideal' material, and a trade-off needs to be made between social impact, environmental impact, technological properties, and cost.

Keywords: Electronics Fabrication, PCBA Fabrication, Social Impact, Sustainability

Master's dissertation submitted in order to obtain the degree of Master of Science in Electrical Engineering - Electronic Circuits and Systems – Academic Year 2025-2026

Abstract (Ned.) – Beoordeling van de sociale gevolgen van de elektronicaproductie

Auteur: Laura Sondakh (02000016) – Promotoren: Prof. dr. ir. Pieter Bauwens and Dr. ir. Maarten Cauwe

De groei van de elektronica-industrie gaat gepaard met toenemende gevolgen. De impact op het milieu wordt reeds onderzocht, maar de sociale gevolgen blijven onderbelicht. In dit werk wordt een werkwijze voorgesteld om de sociale gevolgen van de productie van PCBA's te analyseren. Eerst worden de stappen overlopen voor de productie van IC's, PCB's en afzonderlijke componenten, packaging en assemblage, waarna een overzicht wordt gemaakt van de gebruikte materialen. Voor deze materialen worden de sociale gevolgen geëvalueerd aan de hand van de mijnbouwfase. De gevolgen worden gekwantificeerd op basis van de volgende categorieën: kinderarbeid, informele mijnbouw, gewelddadige conflicten, sterkte van de rechtsstaat, controle van corruptie en menselijke ontwikkeling. Voor elk materiaal worden ze geëvalueerd door aan elk van de vijf meest producerende landen een score toe te kennen en een gewogen gemiddelde te berekenen. Het resultaat is een overzicht van de sociale gevolgen van de verschillende materialen die gebruikt worden voor de productie van elektronica. De materialen met de grootste sociale gevolgen zijn kobalt, tantaal, tin, iridium, ruthenium en chroom. Materialen met lagere sociale gevolgen zijn ijzer, beryllium en lithium. Om in te schatten of veranderingen in het productieproces een groot effect zouden hebben, wordt nagegaan welk aandeel van de globale productie van een materiaal gebruikt wordt binnen de elektronica-industrie. Op basis van deze twee analyses worden kobalt, tantaal en zilver geselecteerd voor een extra analyse, waarin toepassingen en alternatieven worden besproken, rekening houdend met technische eigenschappen en kostprijs. De alternatieven hebben meestal bepaalde nadelen. Voor sommige toepassingen zijn er zelfs geen alternatieven mogelijk. Ten slotte worden de milieu- en sociale gevolgen vergeleken. Hieruit blijkt dat bepaalde materialen met grote sociale gevolgen weinig milieu-gevolgen hebben en vice versa. Het wordt dus duidelijk dat er geen 'ideaal' materiaal bestaat: er is steeds een afweging nodig tussen milieu- en sociale gevolgen, technische eigenschappen en kostprijs.

Kernwoorden: Elektronicaproductie, PCBA-productie, Sociale Gevolgen, Duurzaamheid

Masterproef voorgelegd voor het behalen van de graad master of science in de Electrical Engineering - Electronic Circuits and Systems – Academiejaar 2025-2026

Assessing the Social Impact of Electronics Fabrication

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Abstract

As the electronics industry grows, so does its impact. While the environmental impact has been researched, the social impact has often been overlooked. This work proposes an approach to analyse the social impact of PCBA fabrication. First, the fabrication steps of passive components, ICs and PCBs, packaging, and assembly are considered to compile an overview of essential materials. For each material, social impact is assessed by considering the mining circumstances. The impact is quantified by assessing the following social impact categories: child labour, artisanal and small-scale mining, violent conflict, rule of law, control of corruption, and human development. The social impact categories are assessed per country by assigning a score to the top 5 producing countries and calculating a weighted average. The result is a comprehensive overview of the social impact of various materials used in electronics fabrication. To assess the impact of potential changes within the electronics industry, the share of global production consumed by the electronics industry is assessed for each material. Based on these two analyses, cobalt, tantalum, and silver were selected as three materials of interest for further research. For each of these materials, popular applications and alternative materials are discussed. Finally, the environmental impact and social impact of a selection of materials are compared. Some materials with a high social impact have a low environmental impact, and vice versa. It becomes clear that there is no 'ideal' material, and a trade-off needs to be made between social impact, environmental impact, technological properties, and cost.

Index Terms

Electronics Fabrication, PCBA Fabrication, Social Impact, Sustainability

I. INTRODUCTION

Over the past decades, digital technologies have become more advanced and omnipresent. From toothbrushes to washing machines and cars: as the market for 'smart' devices grows, an increasing number of objects contain electronics in one way or another. However, the social and environmental sustainability of this evolution has often been overlooked. This is especially the case for social sustainability: while the attention to the environmental cost of electronics production has grown [1], the social impact remains underexposed [2]. Regrettably so, as many minerals essential for electronics fabrication come at a high social impact.

The aim of this work is to assess the social impact of electronics fabrication in a systematic and quantified manner, and to provide a tool to aid electronics designers in making informed design choices. To do so, the social impact of the mining of materials essential to the fabrication of Printed Circuit Board Assemblies (PCBAs) is assessed.

This work focuses on the fabrication of PCBAs, as they are the core component of electronics. This facilitates a generalised analysis, not bound to specific industries such as the automotive industry or the consumer electronics industry. A Printed Circuit Board Assembly (PCBA) is understood to be a PCB and the various components assembled onto it.

The scope is defined in the following two ways. First, it is chosen not to include environmental risk factors, in order to focus on the human side of social impact. Second, it is chosen to assess the impact based on the circumstances of the mining of the materials. This stage is chosen for a few reasons: (a)

in social life cycle analyses (SLCAs) of specific applications, risks during the raw material extraction phase are found to be significant [3]; (b) it is a well-defined production step in the supply chain; (c) it is a production step common to all materials.

In literature, such an analysis of the social impact of the electronics industry as a whole, at a global level, has not been found. The Material Change Report [4] makes such an analysis, but is limited to the automotive and consumer electronics industries. While its scope is deemed too limited, its methodology was a valuable inspiration for this work. Other research on the social impact of electronics mainly includes application-specific SLCAs, e.g. [3], which are too specific to make a generalised assessment. Finally, the research on the social impact of mining is extensive; however, it is mostly conducted at the level of individual mines. This work provides a new perspective by assessing the mining circumstances at the level of the producing countries. This enables a global analysis while still accounting for local contexts.

II. MATERIAL SELECTION

A Printed Circuit Board Assembly (PCBA) is understood to be a PCB and the various components assembled onto it. As such, the fabrication of PCBAs consists of the fabrication of the PCB, the fabrication of the various passive components and integrated circuits (ICs) they may contain, the packaging of these components, and their assembly onto the PCB. To select materials, textbooks and papers are consulted to identify the most widely used materials. Important references include:

- Passive components (PC): [5] and [6];
- IC fabrication process (IC): [7], [8], and [9];
- PCB fabrication process (PCB): [7], [10], and [11];
- Packaging (PK): [7], [12], [13], [14], and [15];
- Assembly (AS): [10] and [5].

It is opted to focus on mined materials, so organic materials and plastics, although important throughout the fabrication process, are not included in this work. Additional materials from newer applications (NA), such as hafnium and gallium, are added to the selection. The final selection of materials and their main applications is given in Table I.

Mat.	PC	IC	PCB	PK	AS	NA
Ag	x			x	x	
Al	x	x		x	x	
As		x				
Au				x	x	
B	x	x				
Ba	x					
Be	x					
Bi					x	
Co	x	x		x	x	
Cr	x			x		
Cu	x	x	x	x	x	
Fe	x			x		
Ga						x
Ge						x
Hf		x				
In					x	
La	x					
Li	x				x	
Mn	x					
Mo		x				
Nb	x				x	
Ni	x				x	
P	x	x	x	x		
Pb	x				x	
Pd		x		x		
Pt						x
Rh	x					
Ru	x					
Sb	x	x			x	
Sn	x		x		x	
Ta	x	x				
Ti	x	x		x		
V				x		
W		x		x		
Zn	x				x	
Zr	x					

TABLE I: Materials and their use in the fabrication process; PC = passive components, IC = IC fabrication process, PCB = PCB fabrication process, PK = packaging, AS = Assembly, NA = use in newer applications.

III. SOCIAL IMPACT CATEGORIES & INDICATORS

A. Social Impact Categories

The selected social impact categories are: child labour, artisanal and small-scale mining, violent conflict, rule of law, corruption control, and human development.

Child labour is selected as every form of child labour in mining is categorised under ‘hazardous work’ by the ILO [16], and is considered to be problematic in every form and for each age up until 18.

Another category that is directly related to the mining circumstances is ASM. There is no airtight definition, but the one proposed by the OECD is generally accepted: “Formal or informal mining operations with predominantly simplified forms of exploration, extraction, processing, and transportation. ASM is normally low capital-intensive and uses high labour-intensive technology.”[17] Contrary to child labour, there is no guideline on whether ASM is entirely good or entirely bad. However, it is clear that ASM poses many risks to the safety of miners, especially in regions with high regional conflict or with conflicting industrial mining operations [17][18][19].

Beyond the intersection of ASM and violent conflict, the presence of violent conflict poses many risks to miners and local communities. Furthermore, many violent conflicts are centred around mineral-rich regions, as this mineral richness may help to finance the continuation of the conflict.

Governance and human development are considered to be categories influencing the context in which mining takes place, thus enhancing or mitigating the risks associated with mining. Governance is embodied by the social impact categories ‘rule of law’ and ‘control of corruption’. These categories are considered as they are often cited as factors that reinforce problems in mining and prevent sustainable mining initiatives [20][21]. Similarly, human development is included as a measure for poverty and insecurity, which are also cited as such reinforcing factors [20].

B. Indicators

For each of the social impact categories, relevant indicators are explored. For each indicator, it is important that the source or database: (a) covers all relevant countries in a comparable way; (b) has impartial results and trusted authors; (c) provides a clear description of methodology for transparency. The following indicators are selected:

- Child labour: Database by ILO & UNICEF [22], reporting the percentage of children aged 5 to 17 active in economic activity per country;
- Violent conflict: Heidelberg Conflict Barometer (HCB) [23], reporting the intensity of conflict on a 0-5 scale per region;
- ASM: Database by artisanalmining.org[24], reporting on the percentage of the population active in ASM;
- Rule of Law and Control of Corruption: World Governance Indicators (WGI) published by the World Bank [25], reporting the ‘governance estimate’, which yearly ranks countries for both indicators;

- Human Development [26]: Human Development Index (HDI) provided by the UNDP, reporting an absolute score of Human Development on a scale of 0-100.

C. Assessing Indicators per Material

In order to assess the social impact per material, a relative score of 0-3 per social impact category is assigned to each producing country, based on the value of the indicator for that country. Then, a weighted average is taken of the assigned scores of the top five producing countries, as reported in EU's Raw Materials Information System (RMIS) [27]. This results in a final score per social impact category per material.

For child labour and ASM, the assignment was based on the relative position of each country: 0 for Q1, 1 for Q2, 2 for Q3, and 3 for Q4. For rule of law and control of corruption, the scores were already assigned based on their relative position, so the values are picked in order to correspond to this division in quartiles. This corresponds to the following score assignment:

- Child labour: rate of 4% (0), 4-6.99% (1), 7-15.99% (2), ≥16-100% (3)
- Rule of law and control of corruption: governance estimate of ≥ 1 (0), 0-0.99 (1), -0.99-0 (2), ≤ -1 (3)

For human development and violent conflict, the HDI and the HCB already provide their own scoring, which is incorporated in this work:

- HDI: HDI score of ≥ 0.8 (0), 0.7-0.799 (1), 0.55-0.699 (2), ≤ 0.55 (3)
- HCB: conflict intensity of 3 (0), 3 (1), 4 (2), 5 (3)

IV. SOCIAL IMPACT RESULTS

A. Results

The results of the social impact assessment are shown in Table II. The colour is assigned based on the weighted average score: 0-1 = blue, 1-1.5 = yellow, 1.5-2 = orange, 2-3 = pink. As this assessment is based on the performance of the top five producing countries, the validity is not the same for each material: for some materials, this work covers the full production, while for other materials, only a part is covered. Additionally, some countries are missing in the used data bases. This difference in validity is illustrated by adding the coverage of each material and each indicator, reported inside the brackets in Table II. For gold, a coverage of 50% was not reached across social impact categories. As such, an additional analysis was made by including the top 11 producers, instead of the top 5. These are the results included for gold in the table. The following materials are not included, as they are mainly produced as a by-product of other materials: arsenic is produced as a by-product of the extraction, production and purification of copper, lead, cobalt, and gold; gallium is produced as a by-product of aluminium production; hafnium is produced as a by-product of zirconium production, and germanium and indium are produced as by-products of zinc production. Their social impact should be assessed based on that of the main products.

The two materials with the highest (worst) scores are cobalt and tantalum. Next are tin, antimony, tungsten, bismuth, and barium. Materials with the lowest scores across all social impact categories are zirconium (hafnium), lithium, lead, and platinum.

B. Discussion

Compared to the results of the Material Change Report (MCR) [4], the broad trends are similar. This is no surprise, as a similar methodology is used.

The variation in WGI's rule of law and control of corruption is explained by an evolution in scores since 2018. This results in a lower social impact across materials. For violent conflict, there has also been an evolution since 2018. Furthermore, this work uses a slightly different methodology: it also includes conflicts with an intensity of 3 (violent crises), while the MCR only considers conflicts with an intensity of 4 (limited wars) and 5 (wars). This results in a slightly higher social impact across materials, but the general trend remains the same.

For child labour and ASM, a methodology different from the MCR was followed. In both cases, it was chosen to depart from the rate per country, instead of material-based databases and lists. This results in scores that generally show a higher social impact than in the MCR. For ASM, supplementing the country-based data with material-based data would give a more complete assessment, as the feasibility and profitability of ASM heavily depends on the ore. However, there is no database readily available which contains data on the use of ASM across materials in a comparable way. For child labour, the MCR utilizes an exhaustive list list-of-goods, which is deemed incomplete. As such, it is believed that the metric of child labour rate is more complete to use, which results in higher impact scores.

Gold is considered to be a conflict mineral in US and EU legislation, together with tin, tungsten, and tantalum (3TG) [28]. However, gold does not stand out as having high scores across social impact categories, while cobalt, which is not considered to be a conflict mineral, does. Other due diligence frameworks, such as the OECD's [17], look to move away from only these conflict minerals and plead to include all minerals, to consider their risks. As this work shows that other minerals may have a greater impact, it supports this approach as favourable over only focusing on conflict minerals.

C. Limitations and Recommendations

This work is based on the mining of individual materials. As such, further production steps, such as refining, are not considered. A more extensive analysis could take into account all further production steps up until the materials enter the electronics supply chain.

This assessment is carried out at a country-by-country level. This gives the opportunity to use publicly available databases for the different indicators, and to keep a global overview of the mining of the different materials. A more

extensive analysis could also take into account variations at the local level. Especially in contexts with highly localised legislation or local crises, this might add relevant insights.

Multiple materials may be produced from one mined ore. As such, it might be more correct to analyse different ores, instead of materials. This might also allow to take into account more detailed geographical data, as the presence of different ores is well-documented per regions.

This analysis, based on materials and their mining at a country-by-country level, provides a reliable overview at a global level. It offers a method to efficiently and reliably evaluate the main materials used in PCBA fabrication. Moreover, it provides a good starting point for further, more extensive analysis, and a similar method may be applied to additional materials.

Mat.	CL	ASM	HCB	RL	CC	HDI
Ag	1.56 (60%)	1.61 (60%)	1.31 (60%)	2.13 (60%)	1.43 (60%)	0.83 (60%)
Al	1.24 (84%)	2.35 (84%)	0.68 (84%)	1.63 (84%)	1.42 (84%)	1.22 (84%)
Au	0.95 (52%)	1.66 (61%)	1.05 (61%)	1.59 (61%)	1.17 (61%)	0.53 (61%)
B	0.92 (89%)	2.07 (89%)	1.58 (89%)	1.78 (89%)	1.43 (89%)	0.13 (89%)
Ba	1.12 (72%)	2.32 (82%)	1.26 (82%)	2.05 (82%)	1.68 (82%)	1.22 (82%)
Be	0.71 (99%)	2.05 (99%)	1.11 (99%)	1.40 (99%)	0.52 (99%)	0.48 (99%)
Bi	1.83 (99%)	1.81 (100%)	0.79 (100%)	2.00 (100%)	1.24 (100%)	0.97 (100%)
Co	1.82 (76%)	2.71 (85%)	2.66 (85%)	2.73 (85%)	2.66 (85%)	2.48 (85%)
Cr	0.53 (88%)	1.60 (88%)	1.08 (88%)	1.47 (88%)	2.05 (88%)	0.94 (88%)
Cu	1.55 (61%)	2.15 (61%)	1.30 (61%)	1.62 (61%)	0.95 (61%)	0.77 (61%)
Fe	0.42 (76%)	2.10 (76%)	0.63 (76%)	1.11 (76%)	0.96 (76%)	0.63 (76%)
La	1.46 (94%)	1.97 (97%)	1.18 (97%)	1.80 (97%)	1.00 (97%)	0.85 (97%)
Li	0.55 (98%)	1.94 (98%)	0.44 (98%)	0.72 (98%)	0.30 (98%)	0.16 (98%)
Mn	0.46 (80%)	1.63 (80%)	0.50 (80%)	1.38 (80%)	1.53 (80%)	0.86 (80%)
Mo	1.53 (91%)	1.93 (91%)	1.07 (91%)	1.69 (91%)	0.84 (91%)	0.63 (91%)
Nb	0.01 (99%)	1.88 (100%)	0.95 (100%)	1.88 (100%)	1.88 (100%)	0.94 (100%)
Ni	0 (66%)	2.43 (80%)	1.11 (73%)	1.95 (73%)	1.85 (73%)	0.83 (73%)
P	1.55 (57%)	1.88 (77%)	1.15 (77%)	1.91 (77%)	1.16 (77%)	0.82 (77%)
Pb	1.53 (73%)	1.92 (73%)	0.94 (73%)	1.70 (73%)	0.93 (73%)	0.77 (73%)

Mat.	CL	ASM	HCB	RL	CC	HDI
Pd	0.3 (59%)	1.53 (99%)	1.75 (99%)	1.87 (99%)	1.79 (99%)	0.52 (99%)
Pt	0.26 (87%)	1.25 (98%)	1.18 (98%)	1.34 (98%)	1.95 (98%)	0.90 (98%)
Rh	0.17 (93%)	1.16 (100%)	1.11 (100%)	1.22 (100%)	2.00 (100%)	0.96 (100%)
Ru	0.12 (97%)	1.11 (100%)	1.06 (100%)	1.14 (100%)	2.04 (100%)	1.01 (100%)
Sb	1.78 (52%)	2.00 (91%)	1.24 (91%)	2.34 (91%)	1.74 (91%)	1.10 (91%)
Sn	1.80 (76%)	2.26 (76%)	1.33 (76%)	2.26 (76%)	1.82 (76%)	1.16 (76%)
Ta	1.45 (85%)	2.49 (85%)	2.12 (85%)	2.39 (85%)	2.35 (85%)	1.45 (85%)
Ti	1.18 (66%)	1.62 (66%)	1.13 (66%)	1.62 (66%)	1.28 (66%)	1.06 (66%)
W	1.82 (94%)	1.85 (97%)	0.89 (97%)	2.03 (97%)	1.22 (97%)	0.99 (97%)
V	1.56 (82%)	1.87 (100%)	1.34 (100%)	2.04 (100%)	1.37 (100%)	0.82 (100%)
Zn	1.60 (66%)	2.01 (66%)	1.03 (66%)	1.78 (66%)	1.21 (66%)	0.94 (66%)
Zr	0.57 (85%)	1.84 (85%)	0.64 (85%)	0.92 (85%)	0.99 (85%)	0.88 (85%)

TABLE II: Materials and their performance in different impact categories; CL = child labour, ASM = artisanal and small-scale mining, HCB = heidelberg conflict barometer (violent conflict), RL = rule of law, CC = control of corruption, and HDI = human development index.

V. INDUSTRY CONSUMPTION

To assess the impact of using alternative materials in the electronics industry, an estimate is made of the share of the global production of each material that is used within the electronics industry. This is not straightforward, as there is no consistent reporting available: the included countries differ per source, and there is no consistent terminology. E.g., “high tech engineering”, “machinery”, and “mechanical engineering” are used in different documents, but may partly overlap.

To make an assessment, the ‘use and applications’ data provided by “Solutions for CRITICAL Raw materials - a European Expert Network” in the RMIS[27] is used. In some cases, this data covers global uses; in other cases, it only covers European uses. In the latter case, the data is supplemented with data on the US uses of the material, provided in the United States Geological Survey’s Minerals Yearbook [29]. For each reported use, a qualitative assessment is made about the extent to which it relates to the electronics industry. For example, “automotive” has a rather small overlap with the electronics industry, as a big part of the materials is used for the structure of vehicles, while “integrated circuits” fully overlaps with the electronics industry.

Taking into account the share of the different uses and their overlap with the electronics industry, the consumption of the global production by the electronics industry is considered to be:

- Very High: Beryllium, Copper, Gallium, Ruthenium, Silver, Tantalum;
- High: Aluminium, Indium, Palladium, Platinum, Tin;
- Low: Antimony, Arsenic, Bismuth, Cobalt, Germanium, Gold, Rhodium, Zinc, Zirconium;
- Very Low: Barium, Boron, Chromium, Iron, Lanthanum, Lead, Lithium, Manganese, Molybdenum, Phosphorus, Titanium, Tungsten, Vanadium.

VI. ALTERNATIVES

Based on their high social impact, cobalt and tantalum are selected for an analysis of alternative materials. Based on its high consumption by the electronics industry and its rather high social impact, silver is selected as well.

Cobalt's main applications are as an inductor core, in the silicidation process during IC fabrication, and in Kovar for packaging. Within inductors, cobalt is used as amorphous magnetic core material. These cores are popular to use in electrical power systems as they pose limited eddy current losses and hysteresis losses. Due to the high cost of cobalt, alternatives have been created, such as METGLAS 2650SA1. However, they have a lower saturation induction [30].

During the silicidation process, a layer of silicide is formed to create a low-resistance connection. Titanium silicide has properties similar to that of cobalt silicide: it is stable at high temperatures and has a low resistivity. However, its production process is slower, and thus significantly more expensive than that of cobalt silicide.

Kovar is popular to use in packaging as it has a desirable coefficient of thermal expansion, and it is not too heavy or too expensive. There are many alternative materials, such as molybdenum, copper-tungsten, aluminium, copper, tungsten, and gold. The best alternative depends on the context, as they all have different favourable properties (cost, thermal conductivity, coefficient of thermal expansion, and density).

The main application of tantalum is as a dielectric in electrolytic capacitors, in film resistors, and as a diffusion barrier.

Due to tantalum's high price, its use in capacitors and film resistors has been limited to applications where there are no good alternatives. For electrolytic capacitors, that is in high-energy, high-power applications [6], and for film resistors, that is in applications with a humid environment where stability is important [31].

During back-end of line (BEOL) IC fabrication, tantalum is used as a barrier material between copper and the surrounding dielectric, to prevent undesired connections and short-circuits. Suitable alternatives, such as a molybdenum-based layer are being researched [32]. However, there is also a move towards alternative interconnect materials, as the need for a barrier layer limits downscaling [8].

Silver's main applications are in the surface finishing of PCBs and solder, in die-wire bonding, as the inner electrode in ceramic capacitors, and in electrically conductive adhesives.

Tin-Silver-Copper (SAC) solders are a popular and widely used lead-free solder alternative. Other tin-based alternatives have a higher melting point or are susceptible to corrosion. Indium-based solders and Sn-Zn-Bi may be used as alternatives, depending on the application [33][34].

As a surface finish for PCBs where silver is used, Hot Air Solder Leveling is one option, where alternatives are the alternative solders. Another option is immersion silver. For this process, electroless nickel immersion gold and electroless nickel electroless palladium immersion gold might be a more corrosion resistant alternative. However, these are more expensive and thus mostly used in applications where a high reliability is important, such as aerospace or medical devices. If a conductive surface is not necessary, organic solderability preservatives (OSP) form a good alternative [10].

In die-wire bonding, copper is favoured as a material for wires. However, in some applications its reliability is too low, and gold is used. Due to its lower cost, silver is being researched as an alternative to gold. As such, there are no real alternatives to silver [35].

In ceramic capacitors, silver-palladium alloys are used for the internal electrodes. Due to their high price, the use of base materials based on nickel is already favoured where possible. As such, there are no real alternatives to silver-palladium beyond the advances in nickel-based electrodes [6].

Silver is used as conductive filler in electrically conductive adhesives. Its advantage is that it has a high electrical conductivity. Silver-free alternatives with a similar conductivity are currently limited to graphene. However, as bulk-scale production of graphene is still limited, this is not considered to be a viable alternative (yet) [36].

VII. ENVIRONMENTAL IMPACT

In order to compare environmental impact and social impact, the environmental impact of a selection of materials is extracted from [37]. This paper compares alternative materials for advanced on-chip interconnects based on their technical properties and their environmental impact. While it does not consider the full scope of materials discussed in this work, this paper was selected as an example because of its thorough analysis, both technically and environmentally. First, a selection of suitable alternative interconnect materials is made based on their technological properties. Then, each of the materials' environmental impacts is assessed. This results in the following conclusion:

- Low environmental impact: copper, aluminium, nickel, and cobalt;
- Medium environmental impact: molybdenum and tungsten;
- High environmental impact: platinum, iridium, ruthenium, and rhodium.

It becomes clear that some materials with a high social impact have a low environmental impact (e.g., cobalt), and vice versa (e.g., platinum). This illustrates that there is no 'ideal' choice, and a trade-off must sometimes be made between environmental impact and social impact.

VIII. CONCLUSION

This work provides a methodology to assess the social impact of PCBA fabrication in a structured and quantified

manner. Many essential materials have a high social impact, e.g. cobalt, tantalum, tin, antimony, etc. It is not straightforward to find alternative materials with a lower social impact. Designing will always require a trade-off between technological properties, cost, and sustainability. This work provides a tool to include social impact as a sustainability consideration, next to environmental impact.

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List of abbreviations and symbols

3T	Tin, Tungsten, Tantalum	DS	Drive Sustainability
3TG	Tin, Tungsten, Tantalum, Gold	DUV	Deep Ultra-Violet
AAP	Area Array Packaging	ECA	Electrically Conductive Adhesive
AC	Alternating Current	EEE	Electrical and Electronic Equipment
ACA	Anisotropic Conductive Adhesive	EGS	Electronic-Grade Silicon
ADP	Abiotic resource Depletion Potential	ENIG	Electroless Nickel Immersion Gold
AEC	Aluminium Electrolytic Capacitor	ENEPIG	Electroless Nickel Electroless Palladium Immersion Gold
AMM	Amorphous Magnetic Material		
ARC	Anti-Reflection Coating	EU	European Union
ASM	Artisanal and Small-scale Mining	EUV	Extreme Ultra-Violet lithography
BEOL	Back-End Of Line	FEOL	Front-End Of Line
BGA	Ball Grid Array	GWP	Global Warming Potential
BME	Base Metal Electrode	HASL	Hot Air Solder Leveling
(B)PSG	(Boro)-Phospho-Silicate Glass	HDI	Human Development Index
CAHRA	Conflict-Affected and High-Risk Area	HIHK	Heidelberger Institut für Internationale Konfliktforschung, Heidelberg Institute for International Conflict Research
CMP	Chemical Mechanical Polishing		
CVD	Chemical Vapour Deposition		
DC	Direct Current	IC	Integrated Circuit
DRC	Democratic Republic of the Congo	ICA	Isotropic Conductive Adhesive

ILAB	USA's Department of Labor's Bureau of International Affairs	RDL	Redistribution Layer
ILO	International Labour Organization	RF	Radio Frequency (3 kHz - 300 GHz)
I/O	Input/Output	RMI	Responsible Minerals Initiative
IR	Infra-Red	RMIS	Raw Materials Information System
LCA	Life Cycle Assessment	RoHS	Restriction of Hazardous Substances
LPCVD	Low-Pressure CVD	SA	Sustainability Aspect
LSM	Large-Scale Mining	SAC	Sn-Ag-Cu (tin-silver-copper) alloy
MCR	Material Change Report	SCREEN	Solutions for CRITICAL Raw materials - a European Expert Network
MICS	Multiple Indicator Cluster Survey	SIA	Social Impact Assessment
MLCC	Multi-Layer Ceramic Capacitor	SLCA	Social Life Cycle Analysis
NCA	Non-Conductive Adhesive	SMT	Surface-Mount Technology
OECD	Organisation for Economic Co-operation and Development	TCR	Temperature Coefficient of Resistance
OSP	Organic Solderability Preservative	TEC	Tantalum Electrolytic Capacitor
PCB	Printed Circuit Board	THT	Through Hole Technology
PCBA	Printed Circuit Board Assembly	UN	United Nations
PCD	Poly-Crystalline Diamond	UNICEF	UN agency for Children
PECVD	Plasma-Enhanced CVD	UNDP	UN Development Programme
PGA	Pin Grid Array	USA	United States of America
PME	Precious Metal Electrode	USGS	United States Geological Survey
PVD	Physical Vapour Deposition	WGI	World Governance Indicator
		WS	Water Scarcity

Chapter 1

Introduction

Over the past decades, the increasing presence of digital devices has had a profound impact on our way of life. There are many sides to this evolution that have been researched extensively over the past few years. The following examples of research on the impact of our increasingly digital lives on mental health [1], inequality [2], and education [3] are only a minor selection of the work available.

Within the field of electrical engineering, the focus has primarily been on making this evolution technologically possible. Indeed, over the past few decades, digital technologies have become more advanced and omnipresent, and the chip industry has grown exponentially. From toothbrushes to washing machines and cars: as the market for 'smart' devices grows, an increasing number of objects contain electronics in one way or another. This drives the ever-growing demand for smaller and faster chips, just as predicted (or dictated?) by Gordon Moore, one of the pioneers in semiconductor technology, in his now-famous 'Moore's law'.

While it may be difficult to conceive of the sociological implications of newly developed technologies during their development, there is another, more predictable, impact that is too often overlooked during the development process: both social and environmental sustainability. Regrettably so, as the growth of the chip industry comes with a growing sustainability cost. For example, the growth of the industry is accompanied by an increased use of mineral resources. Additionally, the search for ever-faster and ever-smaller components calls for more specific materials. The use of these materials has many sustainability implications.

Although the attention to the environmental cost of electronics production has grown [4], the social impact remains underexposed [5], even though many minerals essential for electronics fabrication come at a high social impact. Take, for example, tantalum, which is a driver of local armed conflicts in the Democratic Republic of the Congo and linked to child labour [6].

1.1 Aim and Scope

The aim of this work is to assess the social impact of electronics fabrication in a systematic and quantified manner, and to provide a tool to aid electronics designers in making informed design choices. In order to do so, the scope is narrowed down to assess the social impact of the mining of materials essential to the fabrication of Printed Circuit Board Assemblies (PCBAs).

When considering the social impact, this work aims to focus on the human side. Thus, environmental risk factors such as acid discharge to the environment are not considered in this work. This is not to suggest that environmental changes do not have a significant impact on people's lives; however, narrowing down the scope allows for focusing on an aspect that has been less explored in research; the environmental impact of electronics fabrication has been studied more extensively than the social impact, e.g. in [7].

To assess the social impact of electronics fabrication, this work investigates the social impact of the mining of the materials essential to electronics fabrication. I.e., the assessment is based on the circumstances of the raw material extraction phase (mining, primary production) of the materials. It is chosen to focus on this stage of material production for a few reasons: (1) in the social life cycle analysis (SLCA) of specific applications, risks during the raw material extraction phase are found to be significant [8]; (2) it is a well-defined production step in the supply chain; (3) it is a production step common to all materials.

The analysis of the mining circumstances is carried out at the level of the producing countries, and not at the level of the individual mines. This enables a global analysis while still accounting for local contexts. However, it also limits the extent of the analysis: it is not possible to analyse circumstances that vary by mine, such as occupational health and safety.

A Printed Circuit Board Assembly (PCBA) is understood to be a PCB and the various components assembled onto it. As such, the fabrication of PCBAs consists of the fabrication of the PCB, the fabrication of the various passive and active components they may contain, the packaging of these components, and their assembly onto the PCB.

It is chosen to focus on the fabrication of PCBAs in order to encompass the full extent of electronics applications. Indeed, there is a wide range of sectors relying on electronics components, and merely covering the (consumer) electronics industry would result in an incomplete analysis. For example, the electronics used in the automotive and household appliances industries would be disregarded. However, PCBAs are used to introduce electronics in these various industries for diverse applications. By departing from what is needed for the PCBA fabrication process, the dependence of the results on different industries is resolved.

Conversely, focusing on the general fabrication of PCBAs omits many application-specific components. Notably, batteries are not included in this work. While essential to many electronics applications and often linked to having a significant social impact, this would expand the scope of this work beyond what is feasible: there are many different types of batteries, with distinct applications and working principles, diverging from conventional electronics fabrication.

As such, when discussing the applications of lithium and cobalt, the focus is not on their application in lithium-ion batteries, but on their applications within PCB assemblies. This is by no means intended to imply that batteries do not play an important role in electronics, or that there is no social impact associated with them. A separate analysis of batteries would be possible by replicating the methods outlined in this work.

1.2 Existing Research

While analyses of the social impact of specific applications exist, e.g. through Social Life Cycle Analysis (SLCA) [8], in literature, research that assesses the social impact of electronics at a global level has not been found. Additionally, the scope is often different. For example, the social impact for consumers during the use phase of the application is often one of the aspects considered in such a SLCA.

A generalised analysis for the impact, both social and environmental, of the consumer electronics industry and the automotive industry was developed in the Material Change Report (MCR) [9]. This report discusses responsible sourcing within the automotive and consumer electronics industry. The report was drafted by the Dragonfly Initiative (currently TDI) in collaboration with the Responsible Minerals Initiative (RMI), which brings together over 300 companies from over different industries and supports responsible sourcing of minerals globally, and Drive Sustainability (DS), a partnership of ten automotive brands which want to take action for greater sustainability throughout the automotive supply chain.

The MCR illustrates a thorough methodology to assess the social and environmental impact of important materials. It serves as a good inspiration for the methodology followed in this work, as it also investigates the impact of the mining of these materials. However, due to the widespread presence of electronics across many other industries beyond the consumer electronics and automotive industries, this analysis is deemed too limited in scope. Additionally, the report originates from 2018, so a part of the originally used data is outdated. Throughout this work, the report will often be referenced as an important source. Comparisons will be drawn between the findings of this work and those of the MCR.

When discussing the mining industry, there has been extensive research on the social impact; however, much

of this research focuses on one geographical region or one material only [10], [11]. This work aims to improve general insights into the impact of the electronics industry as a whole by considering the global mining industry.

1.3 Structure of this work

In chapter 2, a selection of materials is made. These materials are investigated in the remainder of this work. The chapter starts by giving an introduction to PCBAs, and then analyses the common fabrication processes for conventional PCBAs. For each fabrication process step, important materials are listed. Afterwards, a final selection is made by comparing each listed material and its application to the scope of this work. This chapter aims to provide an overview of the materials most relevant to electronics fabrication.

In chapter 3, social impact is defined. To this end, a set of social impact categories is selected, which is used to define and quantify it. The selected social impact categories are child labour, artisanal and small-scale mining, violent conflict, rule of law, control of corruption, and the human development index. To assess each of the social impact categories, appropriate and transparent indicators are selected. This chapter aims to define social impact categories which can be used for a systematic assessment.

In chapter 4, a score per indicator is assigned for each of the selected materials. The score per indicator is based on the performance of the top five producing countries: each country receives a score per indicator, and the final score per material per indicator is then calculated by taking a weighted average based on the production share of the different countries. This chapter aims to assess the social impact of the materials important to electronics fabrication.

In chapter 5, for each material, the importance of the electronics industry is assessed. I.e., it is analysed which share of global production is consumed by electronics fabrication. This chapter aims to provide an insight into the impact that substituting a certain material during the electronics fabrication process might have.

In chapter 6, for a selection of materials, a detailed analysis is made of the associated social impact and of possible substitutes within the electronics fabrication process. The materials are selected based on their social impact and the importance of the electronics industry to their global consumption. This chapter aims to provide insights into what substitutions may have a large impact, what substitutions are technologically feasible, and at what cost they come.

Finally, in chapter 7, the results of the social impact assessment are compared to their associated environmental impact, for a set of selected materials. This chapter aims to illustrate that there is no “ideal” material, but that impact may be made by weighing different design choices.

Chapter 2

Material selection

To make a selection of materials, the fabrication process of a Printed Circuit Board Assembly (PCBA) is analysed step-by-step. As a PCBA might look very differently depending on the final application, an attempt is made to give an overview that is both complete and clear, i.e., not too detailed.

A PCB assembly consists of a PCB with different components assembled onto it. The components are what make an electrical circuit functional: Integrated Circuits (ICs), resistors, capacitors, inductors, etc. These components are assembled onto a PCB, a printed circuit board. The PCB provides the circuitry to electrically connect the different components, and provides the structure to mechanically support the components and hold them in place. The first section will discuss the fabrication of the PCB.

Broadly, the main components can be divided into two classes: passive components (resistors, capacitors, and inductors) and ICs. The second section will discuss the fabrication of the passive components. Additional components may be added onto the PCBA, depending on the application. For example, diodes and transistors. However, their fabrication is very similar to the one outlined in the front-end-of-line (FEOL) part of IC fabrication. As such, they will not be discussed separately. Other components, such as batteries or connectors, may also be added to a PCBA. However, this is the case for specific applications and lies outside of the scope of this work.

As IC fabrication is an entirely different process, it will be discussed in the third section. The fourth section discusses chip packaging, which starts with the fully fabricated IC and packages it such that it is ready to be assembled onto the PCB, together with the other components. The fifth section finally discusses how these components are assembled onto a PCB.

Throughout this chapter, relevant materials are highlighted with a bold font. The scope of this work contains

all materials that originate from delved ores. The final section provides and discusses the final selection of materials.

2.1 PCB fabrication

The printed circuit board usually has two functions: mechanically supporting the different components that work together and providing electrical conduction paths between circuits. After fabrication, the different components, e.g., packaged ICs and passive components, are assembled onto the PCB.

Typically, the PCB's base materials are the resin system, the reinforcement and the conductive foil. A popular board material is FR-4, which consists of epoxy and woven glass as reinforcement. Layers of FR-4 ('pre-preg') are alternated with a **copper** clad laminate. These inner layers are patterned to obtain the desired electronic connections. The outer layer usually consists of a last pre-preg layer and a copper foil. [12][13]

To create connections between several layers of the PCB or to allow for pin-through-hole mounting, holes are drilled through the PCB. After drilling these holes, the remains at the edges are removed during deburring, and afterwards, residual epoxy is removed from the connections during desmearing. For the drilled holes to become via interconnections between layers, they need to be metalized with **copper**. Additionally, the circuit on the outer surface of the PCB needs to be patterned with copper for good conductivity.

There are two main methods for depositing these metals: electroless copper plating and electroplating. Electroplating is the fastest deposition method, but it can only deposit metal on already electrically conductive surfaces. As such, a thin seed layer of copper is needed. One common method to deposit such a seed layer is electroless copper plating. In electroless copper plating, a thin layer of copper is deposited on all exposed surfaces by submerging the PCB in numerous baths of chemicals. The deposition of electroless copper is possible by using a **palladium** solution as a catalyst [14]. This is a very slow process, resulting in a layer as thin as 1 micron to all exposed areas [12]. Another common method to deposit an electrically conductive seed layer for further electroplating is direct metalization. In this method a thin layer of semiconductor is deposited using, e.g., graphite, conductive polymers, or **palladium** [14].

Once an electrically conductive layer has been deposited, it is possible to use the faster electroplating process to deposit additional copper on the sides of the drill holes and the outer surface. Electroplating is based on electrolysis and uses metal salts, e.g., copper is deposited using **copper sulfate** as an electrolyte. In order to create the circuit pattern on the outer surface, there are two options: panel plating and pattern plating. In panel plating, copper is first deposited everywhere, and then etched back in areas outside of the circuit.

In pattern plating, copper is only deposited selectively where it needs to be. It is a more complex process, including depositing additional layers of **tin** as etch mask, but it allows to fabricate finer lines.

To protect the copper at the outer layer from oxidation, a surface finish is added before other components are soldered onto the board. Surface finishes include Organic Solderability Preservative (OSP), Hot Air Solder Levelling (HASL) (**Sn-Pb** or lead-free alternatives, vide infra), immersion **silver**, immersion **tin**, electroless **nickel** immersion **gold** plating (ENIG), and electroless **gold** plating [15][16].

2.2 Passive Components

One of the types of components assembled onto the PCB is passive components: resistors, capacitors and inductors. Each of the three is discussed separately in the following subsections.

2.2.1 Resistors

A resistor is maybe the most well-known electrical component: it creates resistance R in a circuit. This work examines the materials used for fixed resistors, i.e., with a fixed resistance value. Variable resistors, such as potentiometers, are outside the scope of this work. First, the typical resistors, i.e., surface-mount and through-hole resistors, are discussed. The different resistor types are shown in Figure 2.1. The following types are

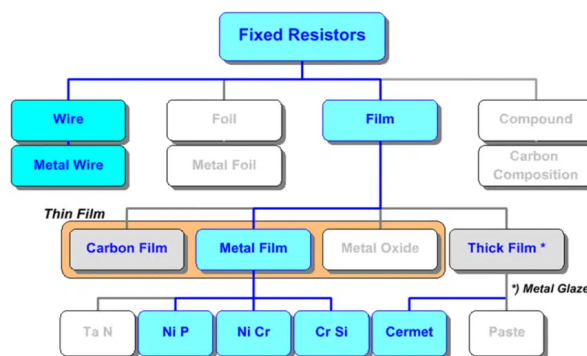


Figure 2.1: Major fixed resistor technologies [17]

examined more closely, as they are the most commonly used: wire-wound, carbon film, metal film, metal oxide and thick film. *Wirewound resistors* consist, as the name suggests, of wound metal wires, and are popular to use at low frequencies. A specific subset, power wirewound resistors, is wound around a bobbin of e.g. porcelain, **alumina**, **beryllia** and glass fibre [17]. The wire is usually made of **nichrome** or **manganin**, both highly resistive alloys [18]. *Carbon film resistors* consist of a thin carbon film wrapped around a ceramic core, often **alumina** [19]. *Metal film resistors*, also known as thin film resistors, consist of metal layers deposited

onto ceramic rods. For the film, the most frequently used materials are **chromium nickel** alloys [17]. To a lesser extent also **tantalum-nitride** alloys are used. Both often contain additives of **aluminium**, **silicon** or **titanium** [20]. For special applications, other alloys may be used as well, such as **tin and antimony** or **gold with platinum** [21]. *Metal oxide resistors* are made by depositing a metal oxide layer on a ceramic core. A popular method is to use a vapour of **tin chloride** (stannic chloride). Finally, *metal glaze resistors*, also known as thick film resistors, consist of a ceramic substrate on which a layer of a paste made of metal particles and glass powder is screenprinted. Popular metal particles are of **ruthenium**, **ruthenium oxide**, **rhodium**, **palladium** or a **tantalum-tin** alloy. [20].

In newer applications, embedded (buried) resistors are used as well. These are made by adding resistive films during the fabrication process of the PCB [22]. An example of such films is Omega Ply RCM [23], which consists of electrodeposited **copper** foil with precision-deposited **nickel phosphorus (NiP)** resistive alloy [24].

2.2.2 Capacitors

Capacitor technologies can be divided into three categories: electrostatic capacitors, electrolytic capacitors and supercapacitors, as shown in Figure 2.2.

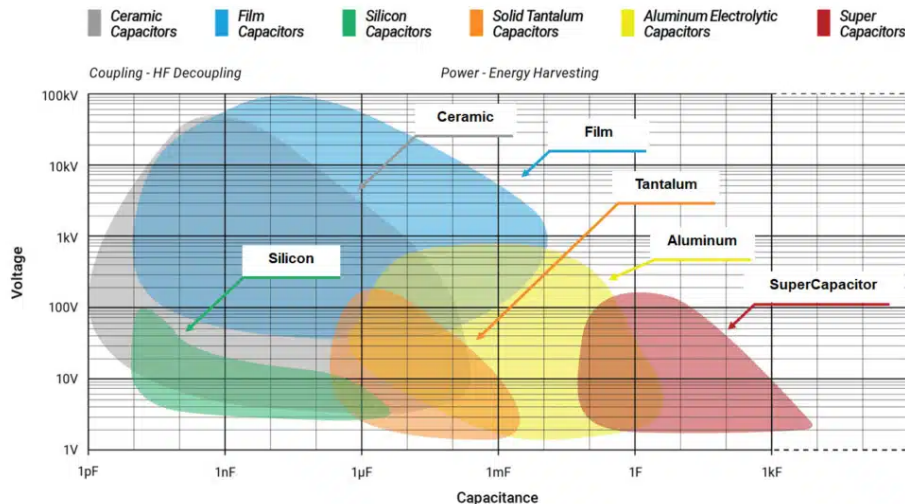


Figure 2.2: Major capacitor technologies [25]

Electrostatic capacitors have a typical structure of Metal-Insulator-Metal, where two electrodes are separated by a dielectric material. They may be divided into three major categories: ceramic capacitors, film capacitors and silicon capacitors [26]. *Ceramic capacitors* are the most commonly used type of electrostatic capacitors. Examples of materials used for the dielectric layer are: **CaZrO₂**, **(Ba,Nd)TiO**, **BaTiO₃**, **(Pb,Lu)(Zr,Ti)O₃** (**PLZT**, **lanthanum-doped lead zirconium titanate**). The electrodes are often made of **copper**, **tin** or **nickel** and

attached by using an adhesive layer of, e.g. **chrome nickel**. For more specialised applications, precious metals like **silver palladium** may be used as well [27]. In *film capacitors*, the dielectric material is a plastic or paper film. The electrodes are made of either a metal film or metalization on the dielectric material directly. In both cases, metals such as **tin**, **zinc** or **aluminium** are used [28]. *Silicon capacitors* are already integrated within the IC features during IC fabrication. As such, silicon capacitors are not taken into consideration in this processing step [29].

Electrolytic Capacitors consist of a cathode, an anode, and an electrolyte in between. The cathode contains a layer of metal oxide, which acts as a dielectric. Due to their construction with an anode and a cathode, electrolytic capacitors are polarised. Electrolytic capacitors are categorised based on the metal used for the cathode (and thus by their dielectric, the oxidised layer). There are two major types: aluminium and tantalum. To a lesser extent, niobium is used as well. Their dielectric layers are Al_2O_3 , Ta_2O_5 and Nb_2O_5 , respectively. The anode is made of a high-purity foil of the same metal. *Aluminium electrolytic capacitors* typically use a wet electrolyte such as **glycol borate**, $\text{C}_2\text{H}_7\text{BO}_4$, or a solid electrolyte, such as a polymer electrolyte. *Tantalum electrolytic capacitors* typically use a wet electrolyte, such as **sulfuric Acid**, H_2SO_4 , or a solid electrolyte, such as **manganese dioxide**, MnO_2 . For both capacitor types, hybrid electrolytes exist as well.

Supercapacitors offer high energy density and reliability. There are two main operation mechanisms: Electrostatic Charge storage and Pseudocapacitance Electrochemical Charge storage. Based on the mechanisms, there are three types of supercapacitors: Electric Double Layer Capacitors (EDLC), with electrostatic charge mechanism dominance, pseudocapacitors, with electrochemical charge dominance and hybrids, with one electrode with electrostatic mechanism dominance and a second with pseudocapacitance mechanism dominance. The electrodes consist of activated carbon and a current collector, which was traditionally conductive rubber, but nowadays is mostly an **aluminium** foil [30]. Three types of electrolyte are used: aqueous-based (e.g. $\text{LiC}_2\text{F}_6\text{NO}_4\text{S}_2$, LiTFSI [31]), organic-based (e.g. **acetonitrile AN** and **propylene carbonate** [31]), or ionic liquids (e.g. $\text{C}_{12}\text{H}_{22}\text{N}_2\text{F}_6\text{S}_2\text{O}_4$, [Pyr 1, 5] [TFSI] [32]).

Buried capacitors exist as well [23]. An example of such buried capacitor is Qnity's *Interra* Embedded Capacitor Laminate, which consists of a thin copper layer electrodeposited onto thin polyimide [33].

2.2.3 Inductors

Most inductors consist of a magnetic core around which a conductive wire is wound. The purpose of the magnetic core is to increase magnetic permeability, which will result in an increase in inductance. There are three main core types: soft iron cores, amorphous magnetic materials, and ferrite core materials. The conductive wire

is typically an insulated **copper** wire. Inductors without a core exist as well; they are called air core conductors [34][35].

Soft iron cores consist of soft **iron** or iron powder mixed with a binder. It is a material that allows reaching a high saturation induction and operating at high frequencies; however, they pose significant hysteresis losses. Amorphous magnetic materials consist of **ferro** or **cobalt** based powdered amorphous alloys. They provide low hysteresis losses and relatively high saturation induction. Finally, the ferrite cores consist of pulverised oxides of, amongst else, **iron**. These are especially suitable for high-frequency applications due to their high material resistivity [35].

It is also possible to fabricate inductors directly onto the PCB. So-called planar inductors are fabricated, for example, by screen printing **iron-based** alloy magnetic pastes onto **copper-clad** laminates [36].

2.3 IC fabrication

The next type of components are Integrated circuits (ICs). Fully packaged ICs ready for assembly onto the PCB are also called 'chips'. These ICs may have various functionalities, ranging from memory chips to functional computing units.

ICs are fabricated on silicon substrates, the so-called wafers. These wafers are made from high-purity silicon. First, silicon is purified, as it is found naturally in a very impure form. It often occurs as quartzite (SiO_2), for example, in sand. Quartzite undergoes multiple refinery steps until electronic-grade silicon (EGS), still polycrystalline, is produced. To go from polycrystalline EGS to monocrystalline silicon, as required for electronic wafer, two methods are used: Czochralski and float zone techniques. After these processes, the result is a large cylindrical ingot of monocrystalline silicon. The ingot is sawn into wafers, which are made completely flat and free of mechanical defects to ensure a clean slate for the fabrication process. These wafer fabrication steps do not rely on metals in significant quantities [37, Chapter 3].

As IC technology is based on semiconductors, doping is an important fabrication step. This process creates the n-doped and p-doped regions, which are fundamental to the electronic functioning of the silicon. In order to produce functional electronic units, the different regions must be patterned correctly and then interconnected through a specific stack of patterned conducting and insulating layers. The fabrication process is mostly photolithography-based as the different layers are patterned using photolithography. The most common fabrication steps used between the photolithography steps are etching, oxidation, deposition, implantation, and planarization [38, Chapter 4]. The fabrication process is divided into two phases: front-end of line (FEOL) and

back-end of line (BEOL). During the FEOL process, the different components are patterned in the silicon. During the BEOL process, the components are connected through interconnections and wiring. Both FEOL and BEOL processes use similar production steps, but on different materials.

2.3.1 Doping

Doping is essential in IC fabrication, as it allows for control of the electrical characteristics of the wafer. It is important that fabrication processes enable precise and localised doping, as it is essential for the correct operation of the created transistors. The two main methods are diffusion and ion implantation. Both follow a similar two-step process, shown in Figure 2.3. For doping of silicon, **boron** and occasionally **gallium** are used for p-type doping and **antimony**, **arsenic**, and **phosphorus** are used for n-type doping.

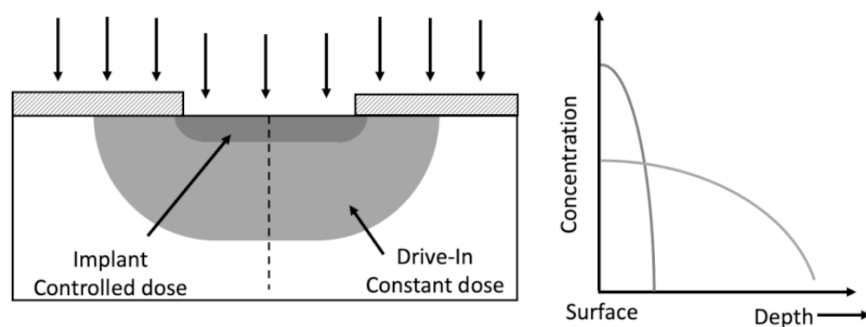


Figure 2.3: Two-step doping process. Taken from [37, p. 296].

Diffusion is an older method for doping wafers. The process consists of two steps: a pre-deposition step and a drive-in step. During pre-deposition, which happens at an elevated temperature, the dopant diffuses into the silicon. The dopant source may be in solid, liquid or gas phase. After pre-deposition, the drive-in happens. In this step, also at an elevated temperature, the diffused dopants diffuse deeper into the silicon lattice. This process is rather slow, but it is possible to dope a batch of up to hundreds of wafers in one cycle. However, the slow process at high temperatures may cause the earlier deposited layers to diffuse further, reducing precision. Additionally, it is hard to precisely control the dose and doping concentration. The drive-in step is isotropic, meaning that it proceeds at the same speed in all directions. As a consequence, it is impossible to achieve narrow but deep doping profiles. As a result, diffusion is mostly replaced by ion implantation [12] [37, Chapter 7].

Ion implantation is also a two-step process. Dopants are introduced in the wafer by ion implantation, and later an annealing step takes place, resulting in controlled diffusion of the dopants. During ion implantation, ions are 'shot' into the wafer. In an ion implantation machine, the ions are extracted from the source, e.g.,

AsH_3 , PH_3 , SbF_3 or BF_3 , using a voltage bias. Then, the desired ions are selected by using a magnetic field to balance the force exerted on the ions and their centrifugal force. The selected ions are then accelerated and aimed at the wafer. This process is shown in Figure 2.4. As such, the initial location, implantation depth and concentration may be controlled precisely. The high energy of the implanted ions may cause lattice damage. After implantation, annealing is used to repair this damage and activate the ions. Depending on the duration, the annealing may also result in further diffusion of the dopants. If diffusion is to be avoided, a rapid thermal anneal (RTA) is used. In this process, the annealing step will only last seconds, but happen at a very high temperature. In oven annealing, there is a longer duration (e.g. 30 minutes) at lower temperatures, which results in dopant diffusion [12] [37, Chapter 8].

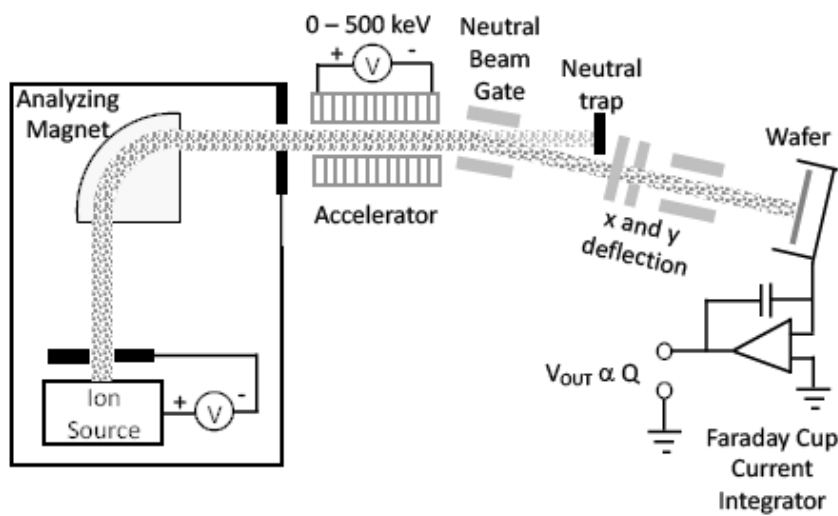


Figure 2.4: Schematic of an ion implanter. Taken from [37, p. 353]

2.3.2 Lithography

An IC is fabricated by stacking different patterned layers of different materials on top of each other. While the basis of ICs is a silicon wafer with doped regions, many other layers of semiconductor material and metals need to be created in order to yield a functional chip. An important component is thus patterning the various layers, i.e., selectively depositing or removing parts of the layers.

These patterns are created through lithography, which is thus arguably the most important process step of IC fabrication. To create patterns in the layers, photoresist is used. The photoresist is first deposited onto the wafer and then patterned by selectively exposing certain parts of the photoresist to light. After the development of the photoresist, only the exposed or unexposed parts remain, depending on the photoresist, effectively forming a pattern for the following production step [37, Chapter 5].

As the feature sizes continue to shrink, lithography machines have become extremely complex and expensive. Currently, in high-volume manufacturing, only projection exposure systems are used. Their operating principle, shown in Figure 2.5, is: a light source illuminates a mask, producing a lighting pattern that is projected onto the photoresist. In between, optical systems (lenses or mirrors) are used to obtain the desired light beams. Several key components can be identified: the light sources, the masks, the wafer exposure system (projection in most cases) and the photoresists.

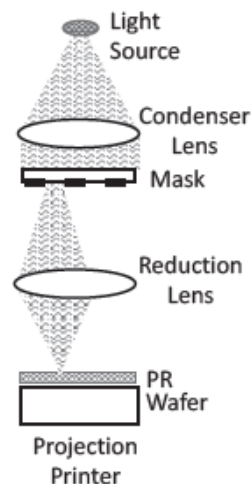


Figure 2.5: Schematic representation of the lithography process. Taken from [37, p. 152]

In order to simplify the design of the optical systems, a monochromatic light source is used. Currently, excimer lasers are commonly used, specifically ArF lasers, replacing the older KrF lasers and even older Hg arc lamps. In the new extreme UV (EUV) lithography systems, a newer light source is used in order to produce 13.5 nm photons: **Sn** plasma pulsed by a CO₂ laser [37, Chapter 5.2.1]. The EUV lithography systems are much bigger and more complex than older systems, but they allow for shrinking feature sizes.

The mask is patterned on a silica plate covered with a thin layer of **chromium** and a layer of photoresist. An antireflection coating (ARC) layer may be used between the chrome and the resist. For EUV, reflecting masks are used. These are made from layers of silicon and **molybdenum**. On top, there is the EUV absorber: a **tantalum boron nitride** film topped by an anti-reflective oxide [37, Chapter 5.2.2].

2.3.3 Etching

Etching is used to remove earlier deposited layers. It usually follows after the deposition of a lithography-defined mask, in order to selectively remove parts of the layer. There are two types of etching commonly used within IC fabrication: wet etching and plasma etching [38, p.56]. Wet etching is generally an isotropic process,

meaning that it proceeds at the same rate in all directions. Dry etching is generally a directed process, meaning that it only etches in one direction, or at least etches much faster in one direction [37, Chapter 9.1].

Wet etching is carried out by dipping a wafer into a wet chemical bath. For proper etching, the process must be selective so that it only etches the target material and not the underlying material, so as not to damage other layers. The etchant thus depends on the material of the layer that needs to be etched and that of the underlying layer(s) that cannot be etched. An example of an etchant is hydrofluoric acid (HF), which etches oxide selectively compared to silicon or silicon nitride. Buffering agents may be added to maintain uniform (but slower) etch rates. Other examples of etchants are potassium hydroxide (KOH) or TMAH, Tetramethylammoniumhydroxide, which result in a directional etch due to their different etch rates for different silicon crystal planes [37, Chapter 9.2].

Dry etching is also known as plasma etching, because it uses a plasma, a mixture of ions, electrons, neutral molecules or atoms, excited molecules and free radicals. Around the wafer, a plasma is created. The etch process is a combination of a chemical and a physical etching process. The excited particles (radicals) are very reactive and will form a chemical bond with the particles that need to be etched. Together, they will be detached from the surface and diffuse out of the wafer. The ionised particles will bombard the surface and reach it at a high speed, striking the molecules of the layer to be etched. Both mechanisms enhance each other, resulting in an efficient method. Again, the etchant depends on the materials to be etched. Examples are fluorines, chlorines and bromides [12] [37, Chapter 9.3].

To achieve steep shapes, plasma etching needs to be enhanced, resulting in Deep Reactive Ion Etching (DRIE). Techniques include the Bosch etch process, where several subsequent plasma etch steps are alternated with thin polymer layers, and the cryogenic process, which happens at very low temperatures [12].

2.3.4 Oxidation

Oxidation is used to create a layer of silicon oxide, which acts as an electronic insulator. The oxide layers are of great importance in the CMOS process. It acts as a spacer, well insulation, a dielectric, a mask... One of the great advantages of using Si as a semiconductor is that a robust, reliable oxide (SiO_2) can be easily grown on its surface. It is also possible to deposit oxide layers, e.g., if it is important to avoid great temperature changes in the wafer, which might be the case in, i.a., back-end of line (BEOL) fabrication. Most of the time, in front-end of line (FEOL) fabrication, oxides are thermally grown. There are two types: wet and dry oxidation. In both cases, gases are introduced at heightened temperatures in a furnace, where the wafers are stacked in a 'boat'. For dry oxidation, O_2 gas is used. For wet oxidation, $\text{H}_2 + \text{O}_2$ are used, and ignited to produce H_2O [12] [37, Chapter

6.2]. The following reactions take place:



2.3.5 Deposition

Deposition is the process of creating an additional layer of a certain material. The deposition processes are either based on chemical processes (chemical vapour deposition, CVD) or physical processes (physical vapour deposition, PVD). In CVD, the source is in the gas phase, and chemical reactions are used to obtain the desired material. In PVD, the source is in solid phase and is already made of the desired material. For the CVD techniques, many types may be distinguished, based on tool type, pressure level, the type of source materials,... The two most used techniques are low-pressure CVD (LPCVD) and plasma-enhanced CVD (PECVD). For PVD, two main types are distinguished: evaporation and sputtering.

In CVD, the reaction of chemicals in the vapour phase is used to form a solid film on the wafer. It is mostly used for dielectrics such as silicon dioxide and silicon nitride, but metals and semiconductors can also be deposited using CVD. To achieve a uniform, pure and heterogeneous layer, the chemical reactions need to occur on the wafer surface. In that case, precursors diffuse through the boundary layer, are adsorbed on the surface, undergo a chemical reaction and form the desired material. If there are byproducts, they are desorbed and diffuse away from the surface [12].

LPCVD processes happen at low pressure. Due to the low pressure, there will be a high gas velocity, and a large amount of precursor will be available. As such, the processes happen in the reaction rate-limited region, meaning that uniformity of temperature is very important to obtain uniform deposition. The deposition temperature is rather high in LPCVD, possibly resulting in additional stress in the layer after cooling and limitations based on the melting temperatures of the materials in the underlying layers. PECVD processes allow lower deposition temperatures by generating more chemically reactive radicals in a plasma. As such, there will be less stress in the film. Additionally, higher deposition speeds are obtained, allowing applications for thicker layers [12].

In PVD, the material is ejected from a solid source and then deposited on the wafer. In evaporation, high temperatures are used to achieve the ejection of the material. In sputtering, plasma is used to achieve the ejection of the material. In general, PVD provides a step coverage that is worse than in CVD [12].

In evaporation, the working pressure and source material dictate which temperature must be used: the working

pressure must match the vapour pressure of the materials at that temperature. Depending on the needed temperature, the method of heating is decided: thermal heating or electron beam heating is used. For example, aluminium and nickel may be evaporated using thermal heating, but tungsten and tantalum need electron beam evaporation. If thermal heating is used, special attention needs to be paid to the container of the source material, the crucible. The material of the crucible is essential: it cannot mix with the material to be evaporated, so there cannot be a chemical reaction, and it cannot melt at the working temperature. If a metal crucible is used, it may be directly heated by high electrical currents, coining the term resistive evaporation. Popular materials are, e.g., **tungsten**, **tantalum** or **molybdenum**, due to their high melting points. However, e.g. aluminium needs a high temperature and will react with tungsten. In that case, a ceramic crucible may be used. The ceramic crucible is placed inside a metal crucible, resulting in indirect heating. Examples of such ceramics are **graphitic C**, **Al₂O₃**, and **boron nitride** [12].

In sputtering, a plasma is used to achieve the ejection of the material. Often, an argon plasma is used. The target is placed at the cathode, the wafer at the anode, and the argon plasma exists in between. The Ar⁺-ions will collide with the target, bringing target atoms into the gas phase. These atoms will diffuse in all directions and deposit, amongst others, onto the wafer. The deposition speed is decided by the flux, which depends on the amount of argon ions hitting the target and on the sputter yield, which depends on the energy of the ion and the target material. Many improvements of this technique exist, for example, magnetron sputtering, RF sputtering and reactive sputtering. Sputtering is possible in many materials: metals, non-metals, refractory oxides, refractory carbides, refractory nitrides,... Compared to evaporation, sputtering has the advantage that it allows alloys to be deposited with a constant composition ratio, and there is better adhesion between the layers. As a disadvantage, sputtering is more expensive [12].

2.3.6 Deposited materials in FEOL and BEOL

All of the production steps discussed above may be used for both FEOL and BEOL fabrication. During FEOL fabrication, where the different components are fabricated on silicon, the most important materials to deposit are those needed in the fabrication steps. For example, in photolithography, a photoresist must be deposited, or nitride may be deposited locally in order to act as an etching mask. Some materials need to be deposited to provide functionality to the chip. For example, silicon oxide may be deposited instead of being created through oxidation. Finally, some materials may need to be deposited in order to chemically react with the underlying layer to create certain layers. For example, during the silicidation process, silicides are created by depositing **titanium**, **cobalt**, **tungsten** or **nickel** onto a silicon layer. There will be a chemical reaction between the metal

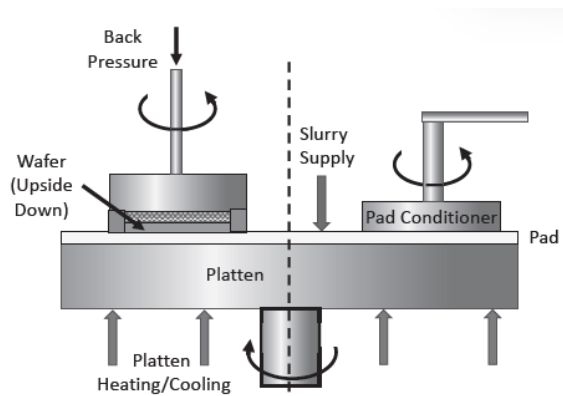


Figure 2.6: CMP planarization tool. Taken from [37, p. 454]

and the silicon, which results in silicide. The remaining metal may be etched back [12].

During BEOL fabrication, the connections between the different silicon components and the outside world are created. The different fabrication steps still require the deposition of various materials, as described above. However, there is the additional deposition of the conducting metals and insulating dielectrics that are needed to create the connections. For example, internal metalization will happen by depositing **aluminium** or **copper**. Currently, copper is mostly used, and the patterning of copper is a major part of modern BEOL fabrication and is often carried out through the Damascene process. Aluminium is used for the bond pads, facilitating the connection to the outside world.

Insulating dielectrics are fabricated by depositing, i.e., **phosphosilicate glass (PSG)** or tetraethyl orthosilicate. There may also be a need to add diffusion barriers between layers. **titanium, TaN, tantalum, TiN** or **tungsten** may be used for this purpose [12][39].

2.3.7 Planarization

Planarization includes many processes which are used to neutralise topography introduced during fabrication steps. It happens at various instants in between the other fabrication steps. This is necessary because the introduced topography causes problems with the focus of the patterning during lithography and step coverage issues during deposition. Techniques include deposition of thick layers of photoresist and etch-back, spin-on-glass layers with etch-back, (B)PSG reflow and CMP. In (B)PSG reflow, **(boro)-phospho-silicate glass** is deposited and baked in an oven to achieve a more planarised surface. As this process happens at high temperatures, it can only be used before metal deposition, i.e. before BEOL processing. CMP, chemical mechanical polishing, is used for polishing and planarizing. It is currently the most used process for planarization, both in FEOL and BEOL fabrication.

A CMP tool, shown in Figure 2.6, consists of three main components: a slurry, a pad and a conditioner. The rotating wafer is pressed onto the rotating pad upside down. The pad contains the slurry and pushes it into the wafer. The slurry is made of chemicals and abrasives, resulting in two simultaneous processes: mechanical abrasion is caused by the rotation, and the pressure between the abrasives (silica) in the slurry and the wafer, and chemical etching is caused by the oxidants (depending on the wafer material) in the slurry. The rotating pad is 'cleaned' using the conditioner to avoid filling up of the apertures of the pad [37, Chapter 9.11] [12].

2.4 Chip Packaging

After all fabrication steps have been completed, the result is a large wafer with many ICs, ranging from a few hundred to several thousand. Each of these chips needs to be cut and then packaged individually before it is ready to be assembled onto a PCB. That is where chip packaging comes into play: it refers to the process of going from a patterned wafer containing many ICs to individually packaged and housed chips, so they are protected components which can be used within bigger systems. There are three main phases: post-fabrication processing, chip assembly, and sealing and housing [12].

A short note on terminology: in this work, IC refers to the circuit fabricated on the wafer, die refers to the individually cut 'bare' wafer containing an IC, and chip refers to the final packaged product, which can be assembled onto the PCB.

2.4.1 Bumping and RDL

The bond pads form the I/O of the IC. However, in preparation for the chip packaging, it might be necessary to add additional features to these bond pads.

In some assembly methods (vide infra), it might be necessary to have bumps on top of the bond pads. These bumps are deposited in the final steps of the IC fabrication and may be made of solder (**Sn-Pb**, **Pb-In**, **Sn-Ag-Cu**, **Sn-Ag**,...), **gold**, **nickel-gold**, **copper**, alloys of **nickel**, **copper**, **palladium**. If lower processing temperatures are required, it is also possible to use polymers. For example, a conductive epoxy bump can be created using **silver**-filled epoxy [40, Chapter 10][12], [41].

During the fabrication of these bumps, under-bump metallization may be added. This could be added to increase conductivity or solderability, or to provide a diffusion barrier, increasing long-term reliability. Typical under bump metalization materials are **TiW-Au**, **Ti-Cu**, **TiW-Cu**, **Cr-CrCu-Cu-Au**, **Al-NiV-Cu**, **Ni-Au** and **Al-NiC-Cu** [40, Chapter 10][12], [41].

Another option is to redistribute the bond pads in order to have them at a convenient location. This is done using redistribution layers (RDLs). The principle is shown in Figure 2.7. The original bond pads were placed at the periphery. By adding a dielectric layer and a metal layer, the bond pads are rerouted towards the centre. This metal layer is mostly **copper**. To the new bond pads, a layer of **gold** may be added through **ENIG** or **ENEPIG**.

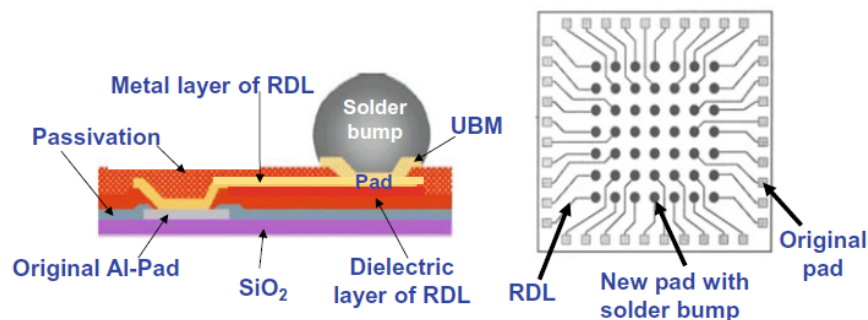


Figure 2.7: RDL principle. Edited from [42, Fig. 3.1]

2.4.2 Post-fabrication processing

Post-fabrication processing refers to the process of coating the wafer after fabrication and dicing the wafer into individual ICs, called dies. The coating applied to the wafer is application-specific and may have an anti-friction, anti-stiction, optical, etc., function. Examples of coating materials are **gold** (reflective optical layer for IR and visible light), **molybdenum polysilicon** (reflective optical layer for EUV), hydromorphic monolayers (anti-friction layer), etc. These are deposited using the techniques previously discussed, or by spin-coating [12].

Dicing is the process of cutting the wafer into individual dies. This process must be precise and cannot leave defects, stress or strain in the individual dies, as this would reduce or even remove their functionality. Examples of such defects are chipping and peeling. The saw blade is thus crucial for the quality of the dicing process. Polycrystalline diamond (PCD) blades achieve optimal performance, as they result in a low amount of defects, and they have a rather long life. As for the bond material of the saw, there are several options, including resin, (electroplated) **nickel**, and **nickel-cobalt**. The best choice depends on the exact composition of the wafer [43].

2.4.3 Chip assembly

After dicing, the individual dies are packaged so that they become more robust and can be assembled onto the PCB without the risk of damaging the fragile die itself. The first step is first-level chip assembly, where the die is connected to the package. In this step, it is very important that the electronic inputs and outputs of the

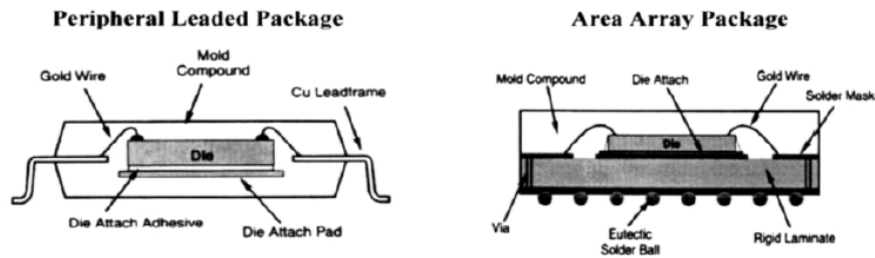


Figure 2.8: Peripheral leaded package vs Area Array package. Taken from [40, p. 36]

die are connected to the relevant ports of the package. There are two main methods for chip assembly: die & wire-bonding and flip-chip assembly.

2.4.3.1 Packaging types

There are two main packaging types: area array, e.g., BGA, or peripheral array, e.g., lead frame. In area array packaging, the I/O is distributed uniformly over the area of the die. This allows for a higher amount of I/O. In area array packaging, the packaging substrate is typically an organic substrate, and the most common assembly type is flip-chip [40, Chapter 3] [12].

In peripheral array packaging, the I/O is transferred through one metal structure inside and outside of the chip package. The I/O lies along the periphery. The difference between the packaging types is shown in Figure 2.8. In peripheral array packaging, the packaging substrate is typically a lead frame. Wire bonding and flip-chip may both be used for peripheral array packaging [40, Chapter 3] [12].

2.4.3.2 Wire bonding

In wire bonding, the dies are placed face-up on top of the packaging substrate, i.e., the back of the die lies on the face of the substrate. The electronic connections are then formed by connecting a wire between the bond pads on the die and the contact pads on the packaging substrate, as shown in Figure Figure 2.9.

First, the die is attached to the substrate through means of a layer of solder or a conductive adhesive. This is called the die attachment. Then, the actual wire bonding takes place, connecting the die's bond pads to the correct contact pads on the substrate. There are two main processes for wire bonding, divided based on the attachment of the wire to the die. A first common process is ball bonding, where the end of the wire is molten into a ball before it is attached to the die. A second common process is wedge bonding, where the wire is connected to the die by pressing its end into the die.

In both of these processes, the mechanism for creating the bond may be one of the following: thermo-compression

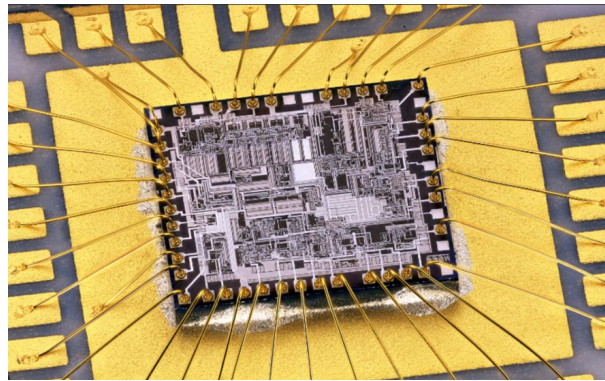


Figure 2.9: Example of die & wire-bonding. The die lies face-up at the centre of the yellow housing substrate. The wires connect the die I/O to the contact pads of the substrate. Picture taken from [44].

(heat and pressure), ultrasonic (ultrasonic energy and pressure), and thermosone (heat, ultrasonic energy, and pressure). There is a wide range of materials used for the wire and the contact pads. Popular choices include **gold** or **aluminium** wires and pads. Other options are (alloys containing) **copper**, **silver**, **palladium** or **nickel** in either the wires or the pads [12] [39].

2.4.3.3 Flip-chip

In flip chip, the dies are assembled face-down ('flipped') onto the substrate, i.e. the face of the die lies on the face of the substrate. This principle is shown in Figure 2.10. The electrical connection between the die and the packaging happens through conductive bumps. The fabrication of these bumps is discussed in subsection 2.4.1.

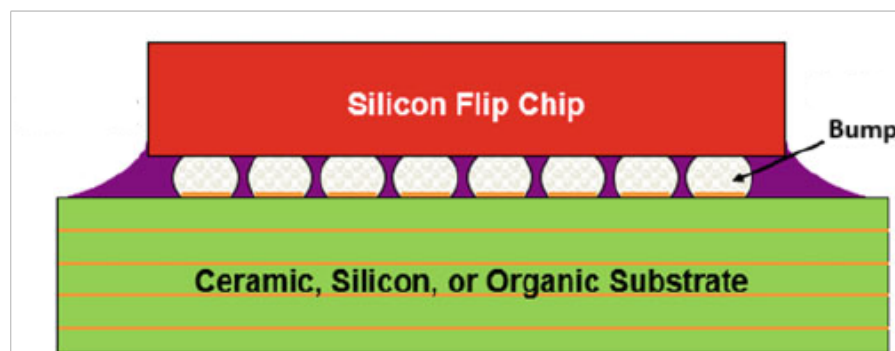


Figure 2.10: Flip chip principle. The red die is assembled face-down onto the green substrate. The grey bumps provide the electrical connection between the die and the orange contact pads on the substrate. The purple underfill provides mechanical stability. Edited from [41, p. 4]

The die is flipped, and the bumps need to be connected to the substrate contact pads. Two common methods to connect the bump and the packaging are: solder reflow and adhesive attachment. In solder reflow, the component's solder bumps are more or less aligned to the contact pads of the substrate. Then, the complete

system is heated, so the solder bumps start to liquidify ('flow') and self-align to the contact pads. When heating is removed, the bumps cool down and solidify at the correct location, resulting in a complete bond and aligned components. This method results in very stable contacts, and it is possible to rework the alignment by detaching and re-attaching the die using heat. To increase mechanical stability and reduce stress due to the mismatch in coefficients of thermal expansion of the different materials, an adhesive underfill may be used between the bumps. These filler materials are not conductive and are applied before or after the solder process, depending on the underfill material [40, Chapter 11] [45].

A disadvantage of solder reflow is that it needs heat. In applications where heat should be avoided, it is possible to use adhesives for attachment. Three types of adhesives are distinguished: isotropic conductive adhesive (ICA), anisotropic conductive adhesive (ACA), and non-conductive adhesive (NCA). In ICA, there is conduction in all directions. As such, it is important that the conductive paste is only added onto the substrate contact pads. The conductive epoxy, consisting of epoxy and, e.g., **silver** flakes, is usually stencil printed onto the housing substrate. There is no self-alignment, so the placement must be precise. After placement, the ICA is cured. Similar to the solder process, underfill is added afterwards to enhance reliability and robustness. Between the curing of the ICA and the addition of underfill, the assembly is very fragile [40, Chapter 11.7] [12].

In ACA, there is only conduction in one direction (i.e., perpendicular to the substrate / die surface). As such, it is possible to add the adhesive to the full substrate. The adhesive consists of conductive beads (e.g. Ni or Au) within an epoxy adhesive. After adhesive application, the die bumps are aligned to the contact pads on the substrate, and bonding is obtained using thermocompression. In NCA, the adhesive contains no conducting filler. In this case, the electrical contact is obtained by ensuring direct contact of the bumps and the contact pads on the substrate. So, the adhesive is added to the substrate, the die and the substrate are aligned, and then connected through thermocompression. NCA is the most cost-effective flip-chip process, but has a lower reliability due to the absence of a conducting material to bond the pad and the bump together. In both ACA and NCA, no underfill is needed, as the adhesive is applied to the full die surface [40, Chapter 11.7] [12].

2.4.4 Housing and sealing

The electrical connection of the die's I/O and the package's I/O is, of course, only one part of the packaging process. The second part is to fabricate the rest of the package, which will protect the fragile die during second-level assembly onto the PCB. The packaging must be appropriately selected for each application in order to result in a robust chip.

It is possible to distinguish different types based on the main packaging materials. Each of the materials

provides different advantages in terms of sealing, electromagnetic properties, price, etc. The most common material types are ceramics, plastic or metal.

A ceramic housing, e.g. produced of Al_2O_3 , has the advantage that it provides good hermetic sealing, but it is very expensive. In ceramic housings, the die is bonded directly to the conductor and a metal lid is soldered on. Plastic housings are cheap, but not hermetic. They are fabricated by first bonding the die to a metal frame, often made of **copper**, **copper alloys**, or **Fe-Ni alloys**, and then injection moulding the rest of the housing. Finally, metal housing provides high thermal conductivity, good cooling, and electromagnetic sealing. In a metal housing, the die is also bonded directly to the conductor, and a lid is soldered on. A popular metal for housing is **Kovar**, a **Ni-Co alloy** [12], [40].

2.5 Component Assembly

Once the chips are fully packaged, they may be assembled onto the PCB, together with the passive components and other components. This phase may also be called second-level assembly.

There are two main methods to assemble components onto the PCB: through-hole technology (THT) and surface-mount technology (SMT), shown in Figure 2.11. In THT, the housing may later be assembled onto, e.g., a PCB by pushing its leads through holes and soldering them. In SMT, the housing may later be assembled onto, e.g., a PCB by placing its (shorter) leads on top of the substrate. An advantage of SMT is that no holes need to be fabricated on the substrate, and that both sides of the substrate can be used.

In THT, the leads are usually made of **tin-coated copper**, and they are inserted into the copper-clad holes fabricated in the PCB. In SMT, components are usually mounted on pads of **tin-lead**, **silver** or **gold-plated copper**. The components' electrodes may consist of several layers. Typical materials are **palladium**, **silver**, **nickel**, **copper**, and **gold**. The top layer may be a solder layer (**Ni, Sn**) [46][47].

In both assembly types, solder is necessary to form an electrical connection between the different components and the PCB. The solder must have electrically conductive properties and a melting point lower than the melting points of all other metals used in the components. Preferably, the melting point is as low as possible. Indeed, the soldering process should not impact, i.e. melt or thermally deform, the other connections in the components [48]. Ideally, solder is eutectic as well, meaning it melts at one clearly defined temperature, instead of melting in a certain range of temperatures [49].

The 63/37 **Sn-Pb** alloy contains optimal properties: it is eutectic and has a relatively low melting point, at 183°C. Other Sn-Pb alloys have very good properties as well. However, as of 2006, the use of lead is forbidden

in the European Union under the Restriction of Hazardous Substances (RoHS) Directive [49]. This directive exists to limit the use of hazardous substances, such as lead, mercury and cadmium, in electrical and electronic equipment (EEE). It aims to protect human health and the environment [50]. Similarly, Japan had passed regulations on lead use before the EU, and USA companies were encouraged to reduce their lead usage in return for tax benefits [51]. As a result, for most applications, producers had to switch to lead-free solder. Some critical applications, e.g. for space equipment, are exempt and can still use solder containing lead.

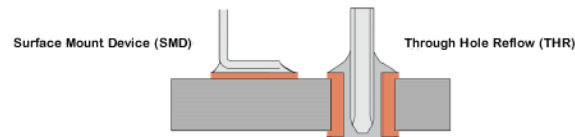


Figure 2.11: Through-hole and surface-mounted device connection, taken from [52].

The search for lead-free solders was not straightforward, as other alloys contain less favourable properties. Additionally, there are not many materials which can be used for solder alloys. Of these, many cannot be used due to legal or practical constraints. Only four materials emerge as the main constituents of solder: **bismuth**, **copper**, **tin** and **zinc**. In smaller quantities **antimony**, which is toxic, and **silver** and **indium**, which are expensive, may be used as well [49]. A popular solder alloy is **Sn-Ag-Cu (SAC)**, to which **Zn**, **Mn** or **Al** may be added to improve characteristics [53].

2.6 Additional materials

In the final selection, the materials indicated in bold throughout the previous sections will be supplemented with materials from less traditional, yet common, PCBA fabrication.

Whereas silicon is the traditional semiconductor on which the electronics industry is based, for newer applications, III-V semiconductors have become increasingly popular, especially **GaAs**, **GaN**, etc. These materials are more expensive than silicon, but provide better optical and electronic properties. They are popular to use in the fabrication of, i.a., high-speed applications, LEDs (GaAs) [54] and power devices (GaN) [55].

Similarly, **germanium**-based semiconductors are used for specific applications. For example, SiGe semiconductors are popular for use in high-speed, low-power applications due to their lower absorption losses [56]. More generally, germanium and GaAs substrates also play an important role in the development of photovoltaics [57]. However, this application is not within the scope of this work.

Hafnium oxide is used as a gate dielectric in sub-45 nm devices. Hafnium oxide has a higher dielectric constant

κ than the traditionally used silicon oxide, which allows smaller sizes and better performance. The hafnium oxide may be doped with, i.a., N, Si, Al, and Ta to increase stability or other properties [58].

As these three materials are important for very relevant modern applications, gallium, germanium, and hafnium will also be taken into account in the remainder of this work.

Additionally, platinum will be added to the final selection due to its use in electronics for memory and data storage applications [59][60].

2.7 Final Selection

For the selection of materials, the scope is defined as follows: materials used for the fabrication of PCB assemblies. This includes materials used during the fabrication process and materials still present on the final PCB assembly. This does not include materials essential for specific manufacturing machines, as this would expand the scope of this work too much. So, e.g., the use of Ni-Co alloys as bond material in saw blades will not be considered in the remainder of this work. This also does not include materials commonly present in the peripherals of common electronic devices, e.g., mica, which is used for the painting of phone casings. Additionally, materials that are not based on mined ores are discarded as well.

The final selection and the main applications per material are shown in Table 2.1. The materials and applications that fall outside the scope of this work have been omitted from the table.

Raw material	Application
Aluminium (Al)	Pure: bond pads, film resistors, inner electrodes film capacitors, anode and cathode of electrolytic capacitors, metalization of IC, contact pads housing, wire in wirebonding Alumina (oxide, Al_2O_3): core of resistors, dielectric of electrolytic capacitors, ceramic housing In alloys: solder, under bump metallization
Antimony (Sb)	In alloys: film resistors, solder In SbF_3 : doping
Arsenic (As)	In AsH_3 : doping
Barium (Ba)	In $(\text{Ba},\text{Nd})\text{TiO}$ and BaTiO_3 : ceramic capacitors
Beryllium (Be)	Beryllia (oxide, BeO): bobbin resistors
Bismuth (Bi)	In alloys: solder
Boron (B)	In glycol borate ($\text{C}_2\text{H}_7\text{BO}_4$): electrolyte of electrolytic capacitors In BF_3 : doping In Boro-phospho-silicate glass: planarization

Raw material	Application
Chromium (Cr)	In nichrome: wire of wirewound resistors, adhesive layer in ceramic capacitors Pure and in alloys: lead frame packaging, under bump metallization
Cobalt (Co)	In alloy: core of inductors Pure: silicidation process In Kovar: metal packaging
Copper (Cu)	Pure: electrodes in SMT devices, through-hole leads, inner electrodes of ceramic capacitors, buried resistors, conductive wire in inductors, metalization in IC BEOL Copper-clad laminate: planar inductors, PCB structure In alloys: solder, wiring and contact pads in wirebonding, flip chip bumps, wire in wirewound resistor, under bump metallization In copper sulfate: electroplating copper
Gallium (Ga)	In GaAs, GaN: LEDs, high-speed applications, power applications
Germanium (Ge)	In Si-Ge: High-speed Low-power applications
Gold (Au)	Pure: Optical coatings, wires in wirebonding, flip chip bumps, contact pads, ENIG for surface finishing of PCBs In alloys: flip chip bumps, under bump metallization
Hafnium (Hf)	In hafnium oxide: gate dielectrics
Iron (Fe)	Pure: core of inductors In alloys: core of inductors, planar inductors, lead frame packaging
Indium (In)	In alloys: solder
Lanthanum (La)	PLZT ((Pb,La)(Zr,Ti)O ₃): ceramic capacitors
Lead (Pb)	PLZT ((Pb,La)(Zr,Ti)O ₃): ceramic capacitors In alloys: solder
Lithium (Li)	In LiTFSI (LiC ₂ F ₆ NO ₄ S ₂): electrolyte of supercapacitors
Manganese (Mn)	In manganine: wire in wirewound resistors In oxide (MnO ₂): electrolyte in electrolytic capacitors
Molybdenum (Mo)	Pure: optical coatings
Nickel (Ni)	Pure: inner electrodes of ceramic capacitors, ENIG for PCB surface finishing of PCBs In alloys: solder, electrodes of SMT devices, wire in wirewound resistors, adhesive layer in ceramic capacitors, wiring and contact pads in wirebonding, flip chip bumps, under bump metallization
Nickel Phosphorus (NiP): buried resistors	
Niobium (Nb)	Pure: anode and cathode in electrolytic capacitors In oxide (Nb ₂ O ₅): dielectric in electrolytic capacitors In alloys: solder

Raw material	Application
Palladium (Pd)	Pure: electrode in SMT devices, metal glaze in resistor, catalyst in electroless copper process In alloys: inner electrode in ceramic capacitors, wiring and contact pads in wirebonding, flip chip bumps
Phosphorus (P)	In PH_3 : doping In alloys: lead frame packaging and metal packaging
Platinum (Pt)	Pure or in alloys: memory and data storage
Rhodium (Rh)	Pure: metal glaze resistors
Ruthenium (Ru)	Pure and in oxide (RuO_2): metal glaze resistors
Silver (Ag)	In alloys: inner electrode in ceramic capacitors, solder, wiring and contact pads in wirebonding Pure: flakes in epoxy for conductive epoxy (e.g. in ICA), surface finish PCB
Tantalum (Ta)	Pure: diffusion barrier In alloys: film resistors, metal glaze resistors In oxide (Ta_2O_5): dielectric in electrolytic capacitors
Tin (Sn)	In alloys: solder, metal glaze resistors Pure: through-hole leads, inner electrode in ceramic capacitors, film capacitors, patterning outer layers of PCBs, surface finishing PCBs
Titanium (Ti)	Pure: additive to film resistors In $(\text{Ba,Nd})\text{TiO}$ and BaTiO_3 : ceramic capacitors In TiN: silicidation process, barrier layer in BEOL In alloys: under bump metallization
Tungsten (W)	Pure: barrier layer in BEOL In alloys: under bump metallization
Vanadium (V)	In Al-NiV-Cu: Under bump metalization
Zinc (Zn)	Pure: Inner electrode in film capacitors In alloys: solder
Zirconium (Zr)	In CaZrO_2 : ceramic capacitors

Table 2.1: Materials and their applications in the main process.

Chapter 3

Defining a social impact score

Defining *social impact* is not straightforward. While there are some existing frameworks to assess social impact, the exact interpretation of what social impact is depends on the user of the framework. In this work, social impact is considered to be the presence of violations of human rights and occupational rights, and human well-being is regarded as the absence of these violations.

3.1 Existing frameworks

Two well-known existing frameworks for assessing social impact are Social Impact Assessment and Social Life Cycle Assessment.

3.1.1 Social Impact Assessment

A social impact assessment (SIA) refers to “assessing a broad range of impacts that are likely to be experienced by an equally broad range of social groups as a result of some course of action” [61]. It is mostly used in project approvals as part of the environmental impact statement, where it has a predictive role. There has been a shift to also include it as an ongoing process during the project in order to identify and respond to social impacts that occur during the project implementation [62].

In many places, an SIA is required as part of the environmental impact statement in permit applications for new projects. As such, many local guidelines exist, and the procedure differs slightly from place to place. However, broadly speaking, the procedure is comparable across locations. As an example, the process outlined in the guidelines of the state of Queensland in Australia is summarised[63].

The main steps before activities commence are:

1. Scoping: determining the study area by identifying the potential area of influence for social impacts as a result of the project;
2. Baseline analysis: describing the existing social conditions and trends within the SIA study area as a benchmark;
3. Community and stakeholder engagement: organising a consultative and inclusive engagement programme to consider the needs of the different stakeholder groups;
4. Assessment of impact: identifying and assessing the potential social impacts associated with the project;
5. Impact mitigation and benefit enhancement: developing and documenting social impact mitigation and benefit enhancement measures for the potential social impacts that have been identified;
6. SIA report: reporting on the identified social impacts and the proposed management plan.

Included types of social impact are: changes to community values or the way the community functions, impacts on how people live on a day-to-day basis, impacts on culture, history, and the ability to access cultural resources, impacts on the community's physical safety, quality of life, physical and mental health, etc.

Due to its main application in project permit applications and environmental impact statements, most SIA guidelines are of a localised nature. For example, the impact on the day-to-day life of a community or their access to infrastructure depends on neighbourhood to neighbourhood, even within a single project. As such, it is not an appropriate framework to use in this work, where the goal is to provide an analysis at a global level.

It might be possible to move from the existing guidelines and abstract the SIA framework to one more suitable for this work, but this would extend beyond the scope of this work: community feedback and stakeholder involvement are central to SIA [62]. This could be achieved by qualitative research, e.g., by conducting interviews with local communities impacted by mining, which would require a bottom-up approach, which is not within the scope of this work.

3.1.2 Social Life Cycle Assessment

A second existing framework is social life cycle assessment (SLCA). This framework is more suitable for the analysis of the impact of specific applications than the SIA, as it does not require a bottom-up approach.

Its methodological phases follow those of a traditional life cycle assessment (LCA) [64]:

1. Goal definition: assessing how human well-being is affected by products or systems throughout their life cycle;
2. Scope definition: defining which parts of the life cycles, which processes, and which social impacts will be analysed;
3. Inventory analysis: making an inventory of data (indicators) that are available and relevant to the aspects of social impact under assessment;
4. Impact assessment: classification of the inventory to know why each type of data is collected and to what it contributes, linking the indicators to impact categories, and normalising and weighting the results;
5. Interpretation: analysing the results of the other phases.

Possible social impacts included in SLCA are divided into three categories: worker-related issues, society-related issues, and product user-related issues. Examples of worker-related issues are non-discrimination, child labour, physical working conditions, level and regularity of wages, etc. Examples of society-related issues are corruption, development support and investments in society, local community acceptance of the company, etc. Examples of product user-related issues are consumer health and safety, ethical guidelines for advertisement of the product, the availability of product information, etc. [64].

As the SLCA is developed to make an assessment of the social impact of an application throughout its entire life cycle, it assesses many aspects that are not relevant to this work, which only focuses on the extractive phase. Additionally, the social impacts proposed in [64] that could be relevant to the extractive phase are too location-specific to use in this work. For example, local community acceptance of the company, and the level and regularity of wages.

There are some aspects which may be implemented in this work: the broad structure of an SLCA and some social impacts, such as corruption and child labour. These aspects were applied to the mining phase and then considered as an inspiration for the framework proposed in this work.

3.2 Proposed framework

In order to allow for general applicability and to allow comparison between materials, it is important to find a well-defined approach which is the same for all materials and which is applicable at a global level.

3.2.1 Material Change Report

A lot of inspiration is drawn from the Material Change Report, published by the Dragonfly Initiative, in collaboration with the Responsible Mining Initiative and Drive Sustainability in 2018 [9]. The report covers an overview of essential raw materials for the automotive industry and the consumer electronics industry, and discusses their importance to the industries and their associated environmental, social and governance (ESG) issues. Its approach to finding the ESG issues is to define a set of concrete indicators and assign a score to all countries for each indicator. Then, for each material, a weighted average of the scores of the top-producing countries is calculated, resulting in a score per indicator per material [9]. This is the approach that will also be used in this work.

This work will use a similar framework in order to assess the social impact of the mining of materials important to electronics fabrication at a global level. While a similar framework is used, this work adds to the Material Change Report (MCR) in two ways. First, it uses updated data. The top-producing countries and their shares may have changed, or the values assigned to a country per indicator may have changed, as the world constantly changes. This work uses, where possible, more up-to-date data. Additionally, the MCR is deemed to be too limited as it only discusses materials important for the Consumer Electronics and Automotive industries. This work tries to provide a more general list of materials by focusing on PCB assemblies (PCBAs), which also exist, e.g., in the Household Appliances industry.

3.2.2 Social Impact Categories

The selection of social impact categories is an important aspect of assessing social impact. In order to make such a selection, inspiration is drawn from the MCR and from typical SLCA social impact categories.

The MCR proposes the following categories[9]:

- artisanal and small-scale mining (ASM),
- child labour and forced labour,
- countries with weak rule of law,
- countries experiencing corruption,
- countries experiencing high-intensity conflict,
- incidences of conflict with indigenous peoples (b),
- incidences of overlap with areas of conservation importance (a),
- potential for acid discharge to the environment (a),
- potential for harm from hazardous materials and chemicals (a),
- preconditions for radioactive materials in ores and tailings (a).

Social impact categories typically included in SLCA are [64]:

- Worker-related issues;
 - Non-discrimination (b),
 - Freedom of association and collective bargaining (b),
 - Child labour, including hazardous child labour,
 - Forced and compulsory labour,
 - Level and regularity of wages and benefits (b),
 - Physical working conditions,
 - Psychological working conditions,
 - Training and education of employees (b).
- Society-related issues;
 - Corruption,
 - Development support and investments in society (b),
 - Local community acceptance of company (b),
 - Company commitment to sustainability issues (b).
- Product user-related issues.
 - Integration of customer health and safety concerns in product (c),
 - Availability of product information to product users (c),
 - Ethical guidelines for advertisement of product (c).

This work focuses on the social impact. As such, categories regarding environmental impact, indicated by (a), are not taken into account, however important. Governance is considered to be a part of social impact. Additionally, as this work is based on a country-by-country assessment, highly localised issues that might even depend on the specific company, indicated by (b), are not taken into account. Finally, categories that are tied to life cycle steps beyond mining, indicated by (c), are not considered in this work.

The final selected categories are: Child Labour, Artisanal and Small-scale Mining (ASM), Violent Conflict, Corruption Control, Rule of Law, and the Human Development Index (HDI). These are in line with the remaining categories of the MCR and SLCA.

Child Labour may be considered the only direct indicator of violations of human and workers' rights. ASM and violent conflict are considered to be immediate risk factors. HDI, control of corruption and rule of law are considered to be underlying conditions, creating an environment where child labour, ASM and violent conflict are more likely.

While Forced Labour is also a clear violation of human rights, it is decided to not include it as a separate factor as it heavily overlaps with other included social impact categories. For example, a large part of the data made available by the International Labour Organisation (ILO) focuses on forced labour by children. This data is already included in child labour. It also often occurs in combination with high corruption or the presence of violent conflict [65]. As such, it is not believed that the inclusion of this impact category would provide more insights.

3.2.3 Framework

Broadly speaking, the framework outlined in this work follows the structure of an SLCA. This work proposes specific indicators and social impact categories to describe the social impact of electronics fabrication.

The scope of this work is the mining or extraction of materials that are important to electronics fabrication at a global level. The analysed social impact categories are child labour, artisanal and small-scale mining, violent conflict, control of corruption, rule of law, and human development index. The choice of these categories and the corresponding indicators will be elaborated in the remainder of this chapter. The impact assessment and interpretation will be carried out in chapter 4.

In order to report fairly on the different countries, it is important to find fair and trustworthy indicators. The following conditions are formulated to include an indicator: (a) Covers all relevant countries comparably; (b) Has impartial results and generally trusted authors; (c) Has a clear description of methodology for transparency.

3.3 Social Impact Categories

3.3.1 Child Labour

A first social impact category considered in this work is child labour. Article 32 of the Convention on the Rights of the Child states: 'States Parties recognise the right of the child to be protected from economic exploitation and from performing any work that is likely to be hazardous or to interfere with the child's education, or to be harmful to the child's health or physical, mental, spiritual, moral or social development.' [66] As such, the presence of child labour in a mining context, which is inherently hazardous, cannot be accepted.

In order to quantify this social impact category on a country-by-country basis, the national child labour rate is used as an indicator. The database published by UNICEF (United Nations agency for children) in collaboration with the International Labour Organization (ILO) [67] is used. In this database, an estimate is given of the percentage of the population aged under 18 active in economic activity, based on data from 2020 to 2024. There is a differentiation for what is considered to be child labour, and thus what is included in the data, depending on age:

- for children younger than 12 years old, over one hour per week;
- for children between 12 and 15 years old, over 14 hours per week;
- for children between 15 and 18 years old, over 43 hours per week.

Additionally, only the hours active in economic activity are taken into account; household chores are not.

The ILO promotes social justice and internationally recognised human and labour rights. As part of this mission, eradicating child labour is one of their important missions. To allow for differentiation between the child's age and the nature of the work, ILO distinguishes [68]:

- work excluded from minimum age legislation (e.g. household chores), ILO does not look for abolition;
- light work, ILO looks for abolition under the minimum age determined by national legislation (12 or 13 years old);
- non-hazardous work, ILO looks for abolition under the minimum age of employment determined by national legislation (14, 15, or 16 years old);
- hazardous work, ILO looks for abolition under the age of 18;
- unconditional worst forms of child labour, ILO looks for abolition under the age of 18.

Under the unconditional worst forms of child labour fall [68]:

- all forms of slavery or practices similar to slavery;
- involvement of a child in prostitution, pornographic production or pornographic performances;
- involvement of a child in illicit activities, in particular for the production and trafficking of drugs.

Under hazardous work falls 'work which, by its nature or the circumstances in which it is carried out, is likely to harm the health, safety or morals of children'. While the specific definition of what exactly constitutes hazardous work depends on the national legislation, the mining sector is always considered to be hazardous in the ILO's guidelines [68]. As such, this work takes into account all age groups when considering child labour rates.

The UNICEF database only contains information on the child labour rate in a country. It does not specify in which sectors child labour takes place. Globally, child labour in industry (which includes mining) only makes up 13 % of all child labour [69]. However, due to the hazardous nature of mining, even child labour in rather small amounts is considered to be problematic. To justify the use of this data in our work, it is compared to the "List of Goods Produced by Child Labor or Forced Labor" published by the USA's Department of Labor's Bureau of International Affairs (ILAB) [70]. From this comparison, it is clear that there is a correlation between countries with high child labour rates and mining activity, and the countries on this list. For example, Uganda has a high child labour rate of 40%. In [70], child labour in Uganda is flagged within the industries of bricks, cattle, charcoal, coffee, fish, gold, rice, sand, stones, sugarcane, tea, tobacco, and vanilla. From the inclusion of gold, it becomes clear that child labour is present in mining in Uganda. However, it is unclear whether the mining of beryllium, of which Uganda is a top 5 producer, is not included because there is no known related child labour, or because the sector is much smaller. However, it seems highly unlikely that there would not be child labour in beryllium mining, given the widespread presence of child labour in general in Uganda. A similar analysis holds true for other countries with a high child labour rate, e.g. Nigeria (28%), where gold mining is included in the

list, but tantalum mining is not, Zimbabwe (26%), where gold and lithium mining are included in the list, but platinum, palladium, rhodium, ruthenium, and chromium are not, and Guinea (20%), where no child labour in bauxite mining (for aluminium) is reported, while there is research that suggests that child labour does exist in mining in Guinea [71]. As such, it is believed that the metric of child labour rate is more complete to use in this work.

It is unclear from the methodology outlined in [70] what the threshold is for including a product. Additionally, the list only provides data on whether a material is known to be produced by child labour and does not provide data on the extent of the child labour. The inclusion of minerals for countries with a high child labour rate indicates a correlation, even if the range of included minerals seems limited. As such, it is opted to use the child labour rates as the indicator for child labour.

3.3.2 Artisanal and Small-scale Mining (ASM)

3.3.2.1 What is ASM?

There is no airtight definition for what falls under artisanal and small-scale mining. However, there is a consensus that the following definition of the Organisation for Economic Co-operation and Development (OECD) covers the load:

Formal or informal mining operations with predominantly simplified forms of exploration, extraction, processing, and transportation. ASM is normally low-capital-intensive and uses high labour-intensive technology. "ASM" can include men and women working on an individual basis as well as those working in family groups, in partnership, or as members of cooperatives or other types of legal associations and enterprises involving hundreds or even thousands of miners. For example, it is common for work groups of 4-10 individuals, sometimes in family units, to share tasks at a single point of mineral extraction (e.g. excavating one tunnel). At the organizational level, groups of 30-300 miners are common, extracting jointly one mineral deposit (e.g. working in different tunnels), and sometimes sharing processing facilities. [65]

ASM exists as opposed to industrial mining, or large-scale mining (LSM), which uses mechanised processes at a large scale and is carried out by formal mining companies. Medium-scale mining covers the mines which are neither ASM nor LSM.

As becomes clear from the definition by the OECD, ASM exists in many shapes and forms. Combined with the big regional differences, it is difficult to unequivocally describe ASM as 'good' or 'bad'.

3.3.2.2 ASM: good or bad?

A first major contribution to ASM's risks is the fact that it mostly takes place informally. This means that there is very little control over what operations at the mine look like: the lack of occupational safety measures has already led to many casualties in the past, e.g., due to collapsed mines and landslides [72]. The informal nature is an obstacle to good governance, as it is more difficult to find out which person or entity is accountable for a mine. Additionally, this legally grey position of the industry places local miners at the mercy of local actors, such as landowners, local government, and local police, for their livelihood and occupational well-being. For example, illegal 'taxes' may be asked, or they could turn a blind eye to workers' rights violations in turn for bribes [73]. ASM is also at an increased risk of criminal infiltration by organised crime groups, which leads to direct risks for the local miners and their families. This risk increases in areas of violent conflict. [74]

The presence of violent conflict increases other risks of ASM as well. While ASM mines are not usually the subject of armed conflict between two fighting parties, i.e., there is not usually a confrontation between fighting parties to gain control of mines [73], they are at great risk of being subjected to armed interference by non-state parties or security forces, due to their informal, smaller, and less organised nature. Once the mining sites are under the control of non-state parties or security forces, there is an increased risk of the local miners being extorted or being subjected to illegal taxation. Additionally, there is an increased risk of forced labour, sexual violence, and other human rights violations [65].

Next to the risks posed at the mining sites, the presence of violent conflict also impacts the following steps in the supply chain. Due to the informal nature of ASM, minerals must enter the formal supply chain through several steps. For example, in the Kivu region of the Democratic Republic of the Congo, individual miners or informal mining cooperatives sell their minerals to traders, who operate at a local level. Then, dedicated transporters are used to move the minerals to bigger trading hubs, after which the minerals are transported to Kinshasa to legally enter the global supply chain, or smuggled to Rwanda, where they then later enter the global supply chain [75]. The many actors involved in transporting minerals from the mine to the global supply chain are at risk of being victims of the local armed conflict. While the mines are usually not a battle objective for armed groups and security forces, control of the transport routes is. At roadblocks or patrols, ASM actors are charged hefty fees to continue their operations. Additionally, non-state armed groups may extort mines to pay 'safekeeping money' or 'taxes'. In countries with low control of corruption, e.g. in the DRC, these illegal 'taxes' may also be collected by local government officials or government security forces, adding another layer of complexity [73].

It is sometimes stated that large-scale mining (LSM), or industrial mining, is more beneficial to local communit-

ies: their operation is better regulated, and it is easier to control compliance systemically. Additionally, these companies pay taxes and are held to a certain standard in terms of providing socioeconomic infrastructure to the region. However, it has been shown that LSM is not necessarily better than ASM in terms of socioeconomic outcomes, e.g. the poverty in the region [76]. Some research even found a more positive impact of ASM, e.g. on local employment [77]. Additionally, ASM may be perceived as an opportunity for local actors to take charge of the mining process and to keep profits in the local economy, instead of being dependent on the goodwill of the multinationals running big mining sites [78].

In areas where both industrial mining (LSM) and ASM take place, there may arise tensions and (armed) conflict. For example, if ASM takes place within the perimeter of the area included in the mining concession of a company, local authorities may be deployed to protect this perimeter, sometimes ending in violent confrontations [79]. These mining conflicts have a detrimental effect on the socioeconomic reality of local communities [76]. Of course, the presence and nature of these conflicts depend entirely on the local context: how are rules maintained, was there local input when creating and selling concessions, is the LSM providing employment opportunities,...

It is estimated that artisanal mining globally employs 45 million people directly, while it is estimated that industrial mining only directly employs about seven million people globally [80], [81]. In many rural areas, it is even the biggest non-agricultural employer. This, combined with the other positive perspectives on ASM, has led to a growing movement to research and develop programs allowing for the sustainable development of ASM.

A first major obstacle to overcome is the informal status of ASM. Its informal (illegal) nature poses threats to sustainable development, as it makes it very difficult to regulate and enforce occupational and environmental measures [82]. However, to transition from an informal status to a formal one, it is important to include the local complexities and the needs of the different actors. Otherwise, a formalization might push ASM actors into illegality and criminality, undoing the efforts. For example, it is important to keep barriers to legal ASM low, i.e., be available close to the ASM areas, not requiring too many bureaucratic steps,... Overarchingly, weak enforcement of rules and high corruption are detrimental to all efforts to create and maintain a formal framework for ASM [82], [83].

In addition to legal reforms at the level of the country, pathways are being created to allow a controlled and documented entrance of ASM minerals into the supply chain. This allows for fair compensation of the actors on one side, and due diligence checks on the other [65].

On a local scale, many projects are also carried out to increase awareness of occupational safety and environ-

mental impact, and to support local communities in creating responsible mining practices. Research has shown that these initiatives mediate the detrimental effect of the presence of violent conflict on the local miners [73].

From the discussion above, it is clear that ASM is not inherently negative, but that it poses many risks, especially combined with the presence of violent conflict, low enforcement of law and high corruption. As such, ASM is one of the social impact categories considered in this work.

3.3.2.3 ASM Database

As an indicator for ASM, the percentage of the population active in ASM is used. This data is extracted from the database found at artisanalmining.org [84]. This database was compiled by Dr. Felix Hruschka and is joined by the following disclaimer:

This data compilation (database and map) was prepared by Felix Hruschka (author) from published and unpublished sources believed to be reliable. The research for this data compilation is fully independent, as it received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. Data and information are provided as of the indicated date of “last database update” and are subject to revision and update without notice. [...]

Due to the author’s well-respected position within the field of ASM, e.g. through his contributions to the Delve platform and his role as former Chair of the Alliance for Responsible Mining [85], this source is assumed to be trustworthy, even if it is difficult to trace back sources for the data.

Due to the nature of ASM, its prevalence is not distributed evenly amongst all minerals, even within the same geographic region. However, it falls outside the scope of this work to perform an analysis on ASM per material for all materials. In chapter 6, a more detailed analysis is made for a selection of materials.

3.3.3 Violent Conflict

As explored in the previous section, the presence of active conflict in the region increases the risks associated with ASM. That in itself is an argument to look into the state of conflict in the producing countries. Additionally, the presence of minerals and the presence of conflict are sometimes intertwined: the presence may be a driver for conflict, as groups might want to gain control over the mineral riches. The other way around, when there is already an ongoing conflict, fighting parties might turn to mineral resources to fund their war.

The presence of violent conflict in itself brings many risks for human rights violations. Think of sexual violence, child soldiers ... This poses a risk for the local communities. For mining specifically, mining areas seized by

armed groups are at risk of increased extortion, forced labour, and child labour. This increases the risks for local miners in particular.

As an indicator for this social impact category, two have been considered: the conflict-affected and high-risk areas (CAHRAs)[86], as defined by EU Regulation 2017/821, and the Heidelberg Barometer of Active Conflict, which is published yearly by the Heidelberg Institute for International Conflict Research (HIIC) [87].

CAHRAs are defined under EU regulation as follows: ‘Conflict-affected and high-risk areas (CAHRAs) are defined as areas in a state of armed conflict or fragile post-conflict. The definition also covers areas witnessing weak or non-existent governance and security, such as failed states, and widespread and systematic violations of international law, including human rights abuses [88]’. This term was adopted by the EU to create guidance for companies’ due diligence obligations¹, specifically in the context of ethical sourcing of minerals. Thus, it is not surprising that this label provides good input for this work. However, it takes into account many factors other than the presence of violent conflict: weak governance, child labour,... As such, this is not a label that can be used to estimate the degree of violent conflict in a country. Rather, this metric will be used as a sanity check: if a country is considered to be a CAHRA but shows no concerning scores in our system, re-investigation is needed.

The Heidelberg Barometer of Active Conflict is focused solely on the extent to which a region experiences violent conflict. It defines levels of conflict on a scale of intensity, ranging from non-violent to outright war. The five intensity levels are 1 (disputes), 2 (non-violent crises), 3 (violent crises), 4 (limited war), and 5 (war). The intensity levels are assigned based on the conflict means (weapons and personnel) and the conflict consequences (casualties, refugees and destruction). For completeness, the report includes ongoing and past conflicts. For this work, the most recently published version is used: the Heidelberg Conflict Barometer 2024 [87].

3.3.4 Control of Corruption and Rule of Law

Even with all regulations in place to ensure responsible sourcing of minerals, it is of unbearable importance that the reality is in correspondence with these rules. That is where governance comes into place: it creates an underlying context for the issues discussed above. This is the case both for industrial and for artisanal mining.

Specifically in the context of artisanal and small-scale mining, there is the added layer of transitioning from informality to formality [83] and other responsible sourcing efforts at a local level. Not only does a lack of ‘good governance’ give rise to a bigger risk of issues arising during mineral sourcing [90], but experience with

¹a process that enterprises should implement to identify, prevent, and mitigate the actual and potential negative consequences (risks) of their activities[89]

responsible sourcing efforts in the DRC shows that these initiatives are actively undermined by governance challenges [91].

However, the effect of governance issues is not limited to artisanal mining. The treatment of miners in the industrial mining sector is also connected to the enforcement of laws in place for the protection of miners. An example of exploitation of miners in industrial mining due to a lack of good governance (on many levels) is the case of Katanga Mining Limited, a Congolese mining company acquired by Glencore [92]. Despite reports of exploitation of ASM miners and child labour, its operation has remained uninterrupted by authorities, even after children as young as 12 have died in their mines [93]. From the beginning, its operations in the DRC have been intertwined with widespread corruption.

More generally, the presence of industrial mining in countries has also been explicitly related to corruption. It is hypothesised that this is due to the nature of mineral resources: the production is geographically fixed and has a big profit margin [94].

As an indicator of governance, the World Bank's yearly World Governance Indicators (WGIs) are used. Yearly, it analyses the state of governance in all countries around the world. To this end, it considers three core dimensions of governance: (1) the process by which governments are selected, monitored, and replaced; (2) the capacity of the government to formulate and implement sound policies effectively; and (3) the respect of citizens and the state for the institutions that govern economic and social interactions. The three dimensions are broken down in the following indicators: Voice and Accountability, and Political Stability are related to the first one, Government Effectiveness and Regulatory Quality are related to the second one, and Rule of Law and Control of corruption are related to the third one [95].

While all three dimensions are important, the second and third core dimensions are deemed most important for the context of mining circumstances. Of these, the third dimension relates to the actual enforcement of regulation, which is deemed to overarchingly affect the reality at the mining sites.

So, the two indicators considered in this work are Rule of Law and Control of Corruption. They are defined as follows:

Rule of Law (RL): perceptions of the extent to which agents respect and follow the rules of society, including contract enforcement, property rights, the police, courts, and the likelihood of crime and violence; Control of Corruption (CC): perceptions of the extent to which public power is used for private gain, including both petty and grand corruption, as well as capture of the state by elites and private interests. [95]

The World Governance Indicators are calculated yearly, based on a cross-country analysis of 35 sources. The indicators are based on perceived data, which seems particularly relevant for the indicators of Rule of Law and Control of Corruption in relation to the mining risks, as it reflects the situation 'on the ground', which is what ultimately affects the mining circumstances. Using perception-based data facilitates the identification of gaps between policy and practice [95].

For this work, the World Governance Indicators of 2024 are used, which, at the time of consultation, were the most recent available data. The WGI report includes, for each country, both a governance estimate and a governance score. The governance estimate indicates how much higher or lower the absolute score of a country compares to the average that year, and is thus a relative measure. The governance estimate is calculated such that it is normalised with a mean of 0 and has a value between -2.5 and 2.5. The governance scores are an absolute score and allow for comparison across different years and years, while the governance estimate allows for comparison across different countries within a year only [95].

3.3.5 Human Development

Contributing to the broader context in which the mining industry exists in each country, "Human Development" is taken into account, as it is strongly believed that the general standard of living influences the state of the mining industry. For example, research suggests that poverty is intertwined with the state of the mining sector [91]. More generally, HDI is considered to be an indicator of social vulnerability, which is defined in [96] as "the susceptibility of groups and individuals to harm and their ability to respond and mitigate that harm." This social vulnerability adds to the vulnerability of mine workers and their susceptibility to the risks that come with, e.g., ASM.

For this work, the Human Development Index is used as an indicator for human development. The Human Development Index (HDI) is calculated yearly by the UNDP (United Nations Development Programme) and takes into account the following three dimensions: health, education, and standard of living [97]. While there is criticism of the use of the HDI as a measure for 'development', the gross trends are assumed to be valid. Combined with the fact that the UNDP is considered to be a complete and trustworthy source for this work, it is decided that the HDI is a sufficient measure to use. In a next iteration of this work, it is an option to look into other measures of development, e.g., such as those explored in [98].

The HDI data of 2023 is used, available at [97]

Chapter 4

Evaluating social impact for important materials

Now that a selection of materials has been made and appropriate social impact categories and corresponding indicators have been selected, it is possible to make an assessment of the social impact of each of the materials. This chapter outlines the methodology and results, followed by a discussion of the results.

4.1 Methods

For each of the materials selected in section 2.7, the values of the different indicators are calculated. To calculate a score for an indicator of a material, the following approach is used, similar to the one suggested in the Material Change Report [9]:

1. The top 5 primary producing countries of the material are selected based on global production share;
2. For each country:
 - (a) The absolute value of the indicator is extracted from the corresponding database;
 - (b) The absolute value is mapped to a category and a relative score of 0, 1, 2, or 3. A high score corresponds to a high social impact related to the indicator at hand.
3. A final score is calculated by calculating a weighted average of the relative scores, based on the production shares of the corresponding countries. A high score of an indicator corresponds to a higher probability of risks related to the mining of the material.

Note that the combined production share of the top 5 producing countries will be different for all materials. For example, ruthenium is only produced in three countries, so the top 5 producing countries produce 100%

of global primary production. On the other hand, for gold, the top 5 producing countries produce only 42% of global primary production. Additionally, for some countries, there is missing data for one or more indicators. Of course, this has implications for the validity of the results presented in this work. To reflect this fluctuation in validity, 'coverage' will be included. The coverage per material and social impact category corresponds to the share of the global production that is covered by the data included in the calculation of the score.

4.1.1 Collecting Data

The production shares are obtained through the EU's Raw Material Information System (RMIS) [99], which is a database containing information on primary production, secondary production, refinery and trade of most raw materials.

In order to select the top 5 producing countries and their respective shares, data on global primary production is used. 'Primary production' refers to the sourcing of virgin materials, so it does not include recycling. So, all mining is a form of primary production, but mining is not the only form of primary production: materials may also be produced as a by-product of the refinery of other materials. This is the case for germanium and indium (produced as a by-product of zinc), gallium (produced as a by-product of aluminium), hafnium (produced as a by-product of zirconium), and arsenic (produced as a by-product of copper, lead, cobalt, and gold). The analysis of these materials will be tied to the analysis of the main mined material.

The absolute scores for the data are collected as discussed in the previous chapter. The social impact categories and corresponding indicators and sources are summarised in Table 4.1.

Social Impact Category	Database	Unit
Child Labour	ILO's & UNICEF's database [67]	Percentage of children aged 5 to 17 active in economic activity
Violent Conflict	Heidelberg Conflict Barometer (HCB) [87]	Intensity of Conflict on 0-5 scale
Artisanal and Small-scale Mining (ASM)	artisanalmining.org database [84]	Percentage of ASM population (Total people active in ASM divided by country's population)
Rule of Law & Control of Corruption	World Bank's World Governance Indicators (WGI) [100]	Governance Estimate (normally distributed score with mean 0 and values between -2.5 and 2.5, comparing absolute score to average score of that year)
Human Development Index (HDI)	UNDP's HDI database [97]	Absolute score of Human Development on 0-100 scale

Table 4.1: Databases used for social impact categories

4.1.2 Assigning relative scores

4.1.2.1 Child Labour

The database reports the percentages of children aged 5-17 active (for a certain number of hours per week) in economic activity. As discussed above, the threshold of active hours per week depends on age. The database does not contain data for all countries. These countries are discarded when evaluating the score of a material. This results in fluctuations of the coverage, as some of the top 5 producers may not be included in the score calculation.

Defining a good assignment of relative scores to the different percentages is not straightforward. To make a division based on quartiles, a frequency table is made:

Value	#	Value	#	Value	#
0	1	8	4	16	3
1	7	9	3	18	4
2	13	10	2	19	2
3	9	11	3	20	1
4	13	12	1	21	3
5	4	13	4	22	2
6	7	14	1	24	1
7	5	15	4	25-54	13
tot.	109				

The frequency table is divided into quartiles, resulting in the score assignment shown in Table 4.2.

% active in economic activity	Relative Score
< 4%	0
4-7% (7% not included)	1
7-16% (16% not included)	2
≥ 16%	3

Table 4.2: Relative score assignment for Child Labour

4.1.2.2 Artisanal and Small-scale Mining

The database reports the percentage of the population active in ASM. It does not contain data for all countries. These countries are discarded when evaluating the score of a material, lowering the coverage for that indicator.

Again, it is opted to define the assignment based on relative position. The first measure of 'Good' is defined based on the definition used in the database, that countries with less than 0.01% active in ASM are considered

to have no ASM. Then, the rest of the countries are ranked from low to high, and the lowest third corresponds to the percentages linked to '1', and so on. This is shown in Table 4.3.

% active in ASM	Relative Score
< 0.01%	0
0.01-0.5% (0.5% not included)	1
0.5-1% (1% not included)	2
$\geq 1\%$	3

Table 4.3: Relative score assignment for ASM

4.1.2.3 Violent Conflict

In the Heidelberg Conflict Barometer (HCB), the levels of conflict intensity are: (0) No conflict, (1) Disputes, (2) Non-violent crises, (3) Violent crises, (4) Limited wars, and (5) Wars. As this work focuses on violent conflict, conflicts of an intensity lower than 3 are not considered to be of impact.

The HCB reports on the state of conflict in regions. In order to assign a score per country, the highest score of the country is used. As in many cases, conflicts are tied to mineral resources, it is considered to be a valid generalisation. Table 4.4 shows the full assignment of relative scores.

Intensity of Conflict	Relative Score
< 3	0
3	1
4	2
5	3

Table 4.4: Relative score assignment for Violent Conflict

4.1.2.4 World Governance Indicators Rule of Law and Control of Corruption

The WGI's Governance Estimates are reported in a normalised manner: all absolute scores are normalised to a distribution with a mean of 0 and values between -2.5 and 2.5. This allows to easily divide the countries into quartiles. The scores in this work are assigned so that the bottom quartile (worst performance) receives the highest score, and the top quartile (best performance) receives the lowest score. Table 4.5 shows the full assignment of relative scores.

4.1.2.5 Human Development Index

The HDI is reported in an absolute score of 100. The UNDP divides the countries into four human development groups: Very High (≥ 0.8), High (0.7-0.8), Medium (0.55-0.7), and Low (≤ 0.55). As for this indicator, unlike

Governance Estimate	Relative Score
≥ 1	0
0-1 (1 not included)	1
-1 - 0 (0 not included)	2
≤ -1	3

Table 4.5: Relative score assignment for WGI Rule of Law and Control of Corruption

for other indicators, a division into categories is proposed by the publisher; it is decided to follow this logic.

Table 4.6 shows the full assignment of relative scores.

HDI	Relative Score
≥ 0.8	0
0.7 - 0.8 (0.8 not included)	1
0.55-0.7 (0.7 not included)	2
≤ 0.55	3

Table 4.6: Relative score assignment for HDI

4.1.3 Calculating weighted average and coverage

For each social impact category, the weighted average and coverage are calculated based on the production shares of the top five producing countries for which data are available. The method is shown in pseudocode below.

```

for i in list_of_materials:
    weighted_total = 0
    total_coverage = 0
    for j in top_5_producers:
        if j has data for indicator:
            total_coverage += production_share_j
            weighted_total += production_share_j * indicator_score_j
    average_score_material_i = weighted_total / total_coverage
    coverage_for_material_i = total_coverage

```

4.1.4 Accounting for missing data

4.1.4.1 Child Labour

The UNICEF and ILO database does not provide data for Australia, Belgium, Canada, China, Cuba, France, Iran, Japan, Kazakhstan, Morocco, Russia, Tajikistan, Thailand, and the USA.

One of the main sources of the database is the UNICEF Multiple Indicator Cluster Survey (MICS)[101]. For Cuba and Thailand, the last MICS did not include child labour. In China, Iran, and Tajikistan, the last MICS was conducted a long time ago (before 2005). In Morocco, the first MICS edition is still being processed. The Kazakhstan MICS was published in 2025, so it was not yet included in the database (reporting on 2020-2024 data).

Australia, Belgium, Canada, France, Japan, Russia, and the USA are not included in the MICS programme. For Belgium and France, the EU Labour Force Survey (LFS) is used, but this does not contain data on the age group of 5-17, only on two separate age groups of 5-14 and 15-19. As such, no data on the age group of 5-17 is included in the database for these countries. For Australia, Canada, China, Japan, and Russia, a lack of data is reported. It is unclear from the report why no data is reported for the USA [101].

A regional estimate of child labour rate is provided for Europe and Northern America: 2.3% [102]. While not as precise as the other (country-based) data, it is assumed that it is fair to use this average as the child labour rate in Belgium, France, Canada, and the USA.

The Kazakhstan MICS reports a child labour rate of 7.5% [103].

For the remaining countries, no reports by the ILO or UNICEF have been found. So, other sources are explored to find additional data. For China, a paper reports a child labour rate of 7.74% in children between 10 and 15 years old [104]. While it is unclear how these numbers vary for children between 5 and 10, and between 15 and 17, and this is the only source found reporting these numbers, it is decided to use this estimate as the child labour rate for China in our work.

For Iran, a child labour rate of 15% is reported [105]. This figure also includes domestic labour and is thus not comparable to the other reported rates (which report economic activity outside of the household). However, this is based on official government reports, which are contested by NGOs such as Iran Human Rights Monitor [106]. They suggest that the rate may be two or three times higher. As such, the number of 15% is assumed to be valid to use in this work.

For Australia, no data on the exact child labour rate has been found, not in the ILO and UNICEF database, nor in scientific literature. However, it is clear from a report on work amongst youth that the dimensions of hours

worked per week do not come close to the threshold maintained by the ILO. Only for the age group of 5-10 years old (of which 1.8% works), the working hours would be considered to be child labour. Additionally, the mentioned sectors are farming, leaflet delivery, community service... [107], which are not at risk of being jobs in mining. As such, while it is not possible to provide an exact number for the child labour rate, a relative score of '0' is assigned manually.

For Cuba, Japan, Morocco, Russia, Tajikistan, and Thailand, no additional data have been found. They will remain without data in this work, and their contribution will be omitted during the calculation of the score, lowering the coverage of that indicator.

4.1.4.2 ASM

For Australia, Iran, Kazakhstan, Russia, Tajikistan, Turkiye, Ukraine, and the USA, the database reports 'existing, not quantified'. This is in contrast with other countries, where no ASM is reported, corresponding to less than 0.01% of the population being active in ASM. So, in these countries, a rate of at least 0.01% is assumed. However, as the Delve database [108] reports no ASM in these regions, it is assumed that there is not a high rate of ASM either. As such, these countries will be manually assigned a relative score of 1.

4.1.4.3 Primary Production

Some materials are mostly produced as by-products of the production, refinement, or purification of other minerals. In that case, no information on primary production is provided in the RMIS [99]. For these materials, the results need to be interpreted by considering those of the main mineral produced from the same ores.

Germanium [109] and indium [110] are mostly produced from sphalerite, which is the most important ore of zinc. As such, the results for germanium and indium will be equated with the results for zinc. Similarly, the results for gallium will be equated to the results of aluminium, as most gallium is produced from bauxite, an important ore of aluminium [111]. All hafnium is produced from zirconium ores [112], so its results will be equated to the results for zirconium.

For arsenic, it is not as straightforward to map its results from another material: it is produced as a by-product of the production process of copper, lead, cobalt, and gold. As such, no specific mapping will be made; it is left to the reader to decide how to weight these contributors [113].

For phosphorus, no data on primary production is available in the RMIS. As such, the information made available by the US Geological Survey (USGS) will be used. Phosphorus is mainly produced from phosphate rock. In 2025,

250 000 tonnes were produced globally. Of these, the five top producers were: China (110 tonnes), Morocco (36 tonnes), USA (20 tonnes), Russia (14 tonnes), and Jordan (12 tonnes) [114]. This corresponds to a production share of China (44%), Morocco (14.4%), the USA (8%), Russia (5.6%), and Jordan (4.8%), which will be used in the following calculations.

4.2 Results

4.2.1 Top 5 producers

The top 5 producers are shown in Table 4.7. Note: gallium is considered to be a byproduct of aluminium production, and germanium and indium of zinc production. As such, they are not explicitly included in this table. For phosphorus, the data are extracted from the US Mineral Yearbook on Phosphate Rock [114]. For all other materials, the data are extracted from the data on primary production found in the RMIS database [99], as explained in the previous section. For phosphorus, another database is used because the RMIS database did not report on the primary production of phosphorus, and a specific form of phosphorus, elemental phosphorus or white phosphorus, is needed for semiconductor doping. This form is refined from phosphate rock.

Material	Top 5 Producers (production share)
Aluminium (Al)	Australia (27,2%), Guinea (23%), China (18%), Brazil (9,5%), Indonesia (6,8%)
Antimony (Sb)	China (44,1%), Tajikistan (27,8%), Russia (10,5%), Turkiye (4,5%), Australia (3,6%)
Barium (Ba)	India (29,9%), China (26,3%), Kazakhstan (12,1%), Morocco (10,0%), Mexico (3,8%)
Beryllium (Be)	USA (64,3%), China (25,8%), Mozambique (4,9%), Uganda (2,8%), Brazil (1,2%)
Bismuth (Bi)	China (75,2%), Vietnam (19,4%), Kazakhstan (2,3%), Peru (2,3%), Russia (0,4%)
Boron (B)	Turkiye (51,6%), USA (18,3%), Chile (7,4%), Bolivia (6,3%), China (5,1%)
Chromium (Cr)	South Africa (51,3%), Kazakhstan (12,8%), India (11,5%), Turkiye (8,3%), Zimbabwe (4,3%)
Cobalt (Co)	DRC (69,2%), Russia (6,0%), Australia (3,9%), Canada (2,9%), Cuba (2,8%)
Copper (Cu)	Chile (26,3%), Peru (10,7%), DRC (9,0%), China (8,9%), USA (5,7%)
Gold (Au)	China (10,0%), Russia (9,6%), Australia (9,5%), Canada (6,8%), USA (5,7%)
Iron (Fe)	Australia (36,0%), Brazil (16,8%), China (11,9%), India (7,7%), Iran (4,1%)
Lanthanum (La)	China (57,2%), USA (20,1%), Myanmar (11,2%), Australia (5,4%), Thailand (2,7%)
Lead (Pb)	China (43,9%), Australia (10,7%), USA (6,3%), Mexico (6,0%), Peru (5,8%)
Lithium (Li)	Australia (48,9%), Chile (28,0%), China (13,1%), Argentina (5,5%), Brazil (2,4%)
Manganese (Mn)	South Africa (33,5%), Gabon (20,0%), Australia (15,5%), China (6,1%), Ghana (4,4%)

Material	Top 5 Producers (production share)
Molybdenum (Mo)	China (38,3%), Chile (18,5%), USA (15,4%), Peru (12,8%), Mexico (6,1%)
Nickel (Ni)	Indonesia (47,1%), Philippines (13,7%), Russia (6,8%), New Caledonia (6,6%), Australia (5,4%)
Niobium (Nb)	Brazil (92,5%), Canada (6,3%), Russia (0,5%), DRC (0,4%)
Palladium (Pd)	Russia (39,9%), South Africa (39,6%), USA (7,0%), Canada (6,2%), Zimbabwe (5,9%)
Phosphorus (P)	China (44,0%), Morocco (14,4%), USA (8,0%), Russia (5,6%), Jordan (4,8%)
Platinum (Pt)	South Africa (72,9%), Russia (10,8%), Zimbabwe (7,6%), Canada (3,9%), USA (2,3%)
Rhodium (Rh)	South Africa (85,3%), Russia (6,7%), Zimbabwe (5,4%), Canada (2,1%), USA (0,4%)
Ruthenium (Ru)	South Africa (93,2%), Zimbabwe (3,8%), Russia (3,0%)
Silver (Ag)	Mexico (23,6%), China (13,5%), Peru (12,8%), Chile (5,3%), Australia (5,1%)
Tantalum (Ta)	DRC (41,9%), Brazil (19,1%), Rwanda (14,3%), Nigeria (5,8%), China (4,0%)
Tin (Sn)	China (33,6%), Indonesia (12,7%), Myanmar (12,5%), Peru (10,0%), Bolivia (7,2%)
Titanium (Ti)	China (31,0%), Canada (12,6%), Mozambique (8,3%), South Africa (8,1%), Ukraine (6,5%)
Tungsten (W)	China (75,5%), Vietnam (15,8%), Russia (2,7%), Rwanda (1,3%), Bolivia (1,2%)
Vanadium (V)	China (63,1%), Russia (17,3%), South Africa (13,3%), Brazil (5,0%), Kazakhstan (0,9%)
Zinc (Zn)	China (32,0%), Peru (11,9%), Australia (10,2%), India (6,2%), Mexico (5,7%)
Zirconium (Zr)	Australia (39,1%), South Africa (21,7%), China (9,6%), Mozambique (8,4%), Senegal (6,2%)

Table 4.7: Materials and their top 5 producers

4.2.2 Indicator scores per country

In Table 4.8, the value per indicator is given for each country that is a top 5 producer for at least one of the materials. The cell colour corresponds to the assigned relative scores (0 = blue, 1 = yellow, 2 = orange, 3 = pink). Cells with 'ND' refer to no data, i.e., the country was not part of the database. If the 'ND'-cell is coloured grey, it will not be considered in the analysis, lowering the coverage for that indicator. If the value has been manually assigned, as discussed in subsection 4.1.4, it remains an 'ND'-cell, but it will be coloured according to the manual assignment. For nickel, New Caledonia is the fourth producer. As New Caledonia is a French Territory, France will be considered instead in this step and the following.

Country	Child labour %	ASM miners %	HCB	WGI Rule of Law	WGI Corruption	HDI
Argentina	2.0	0.01	1	-0.25	-0.33	0.865
Australia	ND	ND	0	1.47	1.85	0.958

Country	Child labour %	ASM miners %	HCB	WGI Rule of Law	WGI Corruption	HDI
Bolivia	13.0	1.97	3	-1.27	-1.00	0.733
Brazil	2.0	0.40	3	-0.45	-0.41	0.786
Canada	2.3	0.00	2	1.46	1.63	0.939
Chile	4.0	0.37	3	0.69	1.11	0.878
China	7.7	0.64	3	-0.58	0.16	0.797
Cuba	ND	0.05	2	-0.62	-0.23	0.762
DRC	15.0	2.23	5	-1.63	-1.52	0.522
France	2.3	0.01	2	1.42	1.41	0.92
Gabon	5.0	0.22	2	-1.16	-0.94	0.733
Ghana	6.0	3.86	2	0.05	-0.19	0.628
Guinea	20.0	2.67	3	-1.15	-1.17	0.500
India	1.0	1.09	4	-0.04	-0.30	0.685
Indonesia	2.0	1.32	3	-0.21	-0.54	0.728
Iran	15	ND	3	-1.23	-1.15	0.799
Japan	ND	0.00	1	1.51	1.36	0.925
Jordan	1.0	0.00	3	0.23	0.17	0.754
Kazakhstan	7.5	ND	2	-0.38	-0.07	0.837
Madagascar	25.0	2.53	0	-0.88	-1.01	0.487
Mexico	4.0	0.04	4	-1.15	-0.94	0.789
Morocco	ND	0.27	3	-0.37	-0.52	0.710
Mozambique	11.0	2.05	4	-1.19	-1.06	0.493
Myanmar	8.0	0.96	5	-1.81	-1.25	0.609
Nigeria	28.0	0.49	5	-1.01	-1.11	0.560
Peru	16.0	0.30	3	-0.51	-0.72	0.794
Philippines	1.0	0.37	3	-0.57	-0.58	0.720
Russia	ND	ND	5	-1.16	-0.89	0.832
Rwanda	4.0	0.50	3	0.10	0.63	0.578
Senegal	9.0	0.40	3	-0.20	0.11	0.530
South Africa	2.0	0.05	3	0.02	-0.19	0.741
Tajikistan	ND	ND	3	-1.18	-1.22	0.691

Country	Child labour %	ASM miners %	HCB	WGI Rule of Law	WGI Corruption	HDI
Thailand	ND	0.03	3	-0.22	-0.53	0.798
Turkiye	6.0	ND	4	-0.84	-0.56	0.853
Uganda	40.0	0.66	5	-0.74	-1.12	0.582
Ukraine	2.0	ND	5	-0.72	-0.67	0.779
USA	2.3	ND	3	0.96	1.09	0.938
Vietnam	6.0	0.06	2	-0.31	-0.25	0.766
Zimbabwe	26.0	6.73	3	-1.43	-1.25	0.598

Table 4.8: Countries and their performance on indicators

To perform a sanity check on Table 4.8, a cross-check of the countries' performance for violent conflict with the list of conflict-afflicted and high-risk areas (CAHRA) is carried out, as discussed in subsection 3.3.3. The only country included in this work that is not assigned a high score on violent conflict, but is included in the CAHRA list [86], is the Philippines. However, this seems to be contained to only one region in the country, which the Heidelberg Conflict Barometer places at 3. All other countries included in the CAHRA list are assigned a score of 4 or 5 in this work and vice versa. This confirms the validity of using the Heidelberg Conflict Barometer for this work.

4.2.3 Social impact per material

In Table 4.9, the weighted average per parameter is given for each material. The cell colour corresponds to a categorization of the weighted average (0-1 = blue, 1-1.5 = yellow, 1.5-2 = orange, 2-3 = pink). A grey colour indicates that the coverage is too low (less than 50%) to give a valid indication. The coverage is indicated between parentheses.

Material	Child Labour	ASM	HCB	Rule of Law	Corruption	HDI
Aluminium (Al)	1.24 (84%)	2.35 (84%)	0.68 (84%)	1.63 (84%)	1.42 (84%)	1.22 (84%)
Antimony (Sb)	1.78 (52%)	2.00 (91%)	1.24 (91%)	2.34 (91%)	1.74 (91%)	1.10 (91%)
Barium (Ba)	1.12 (72%)	2.32 (82%)	1.26 (82%)	2.05 (82%)	1.68 (82%)	1.22 (82%)
Beryllium (Be)	0.71 (99%)	2.05 (99%)	1.11 (99%)	1.40 (99%)	0.52 (99%)	0.48 (99%)
Bismuth (Bi)	1.83 (99%)	1.81 (100%)	0.79 (100%)	2.00 (100%)	1.24 (100%)	0.97 (100%)
Boron (B)	0.92 (89%)	2.07 (89%)	1.58 (89%)	1.78 (89%)	1.43 (89%)	0.13 (89%)

Material	Child Labour	ASM	HCB	Rule of Law	Corruption	HDI
Chromium (Cr)	0.53 (88%)	1.60 (88%)	1.08 (88%)	1.47 (88%)	2.05 (88%)	0.94 (88%)
Cobalt (Co)	1.82 (76%)	2.71 (85%)	2.66 (85%)	2.73 (85%)	2.66 (85%)	2.48 (85%)
Copper (Cu)	1.55 (61%)	2.15 (61%)	1.30 (61%)	1.62 (61%)	0.95 (61%)	0.77 (61%)
Gold (Au)	0.62 (32%)	1.67 (42%)	1.07 (42%)	1.31 (42%)	0.70 (42%)	0.24 (42%)
Iron (Fe)	0.42 (76%)	2.10 (76%)	0.63 (76%)	1.11 (76%)	0.96 (76%)	0.63 (76%)
Lanthanum (La)	1.46 (94%)	1.97 (97%)	1.18 (97%)	1.80 (97%)	1.00 (97%)	0.85 (97%)
Lead (Pb)	1.53 (73%)	1.92 (73%)	0.94 (73%)	1.70 (73%)	0.93 (73%)	0.77 (73%)
Lithium (Li)	0.55 (98%)	1.94 (98%)	0.44 (98%)	0.72 (98%)	0.30 (98%)	0.16 (98%)
Manganese (Mn)	0.46 (80%)	1.63 (80%)	0.50 (80%)	1.38 (80%)	1.53 (80%)	0.86 (80%)
Molybdenum (Mo)	1.53 (91%)	1.93 (91%)	1.07 (91%)	1.69 (91%)	0.84 (91%)	0.63 (91%)
Nickel (Ni)	0 (66%)	2.43 (80%)	1.11 (73%)	1.95 (73%)	1.85 (73%)	0.83 (73%)
Niobium (Nb)	0.01 (99%)	1.88 (100%)	0.95 (100%)	1.88 (100%)	1.88 (100%)	0.94 (100%)
Palladium (Pd)	0.3 (59%)	1.53 (99%)	1.75 (99%)	1.87 (99%)	1.79 (99%)	0.52 (99%)
Phosphorus (P)	1.55 (57%)	1.88 (77%)	1.15 (77%)	1.91 (77%)	1.16 (77%)	0.82 (77%)
Platinum (Pt)	0.26 (87%)	1.25 (98%)	1.18 (98%)	1.34 (98%)	1.95 (98%)	0.90 (98%)
Rhodium (Rh)	0.17 (93%)	1.16 (100%)	1.11 (100%)	1.22 (100%)	2.00 (100%)	0.96 (100%)
Ruthenium (Ru)	0.12 (97%)	1.11 (100%)	1.06 (100%)	1.14 (100%)	2.04 (100%)	1.01 (100%)
Silver (Ag)	1.56 (60%)	1.61 (60%)	1.31 (60%)	2.13 (60%)	1.43 (60%)	0.83 (60%)
Tantalum (Ta)	1.45 (85%)	2.49 (85%)	2.12 (85%)	2.39 (85%)	2.35 (85%)	1.45 (85%)
Tin (Sn)	1.80 (76%)	2.26 (76%)	1.33 (76%)	2.26 (76%)	1.82 (76%)	1.16 (76%)
Titanium (Ti)	1.18 (66%)	1.62 (66%)	1.13 (66%)	1.62 (66%)	1.28 (66%)	1.06 (66%)
Tungsten (W)	1.82 (94%)	1.85 (97%)	0.89 (97%)	2.03 (97%)	1.22 (97%)	0.99 (97%)
Vanadium (V)	1.56 (82%)	1.87 (100%)	1.34 (100%)	2.04 (100%)	1.37 (100%)	0.82 (100%)
Zinc (Zn)	1.60 (66%)	2.01 (66%)	1.03 (66%)	1.78 (66%)	1.21 (66%)	0.94 (66%)
Zirconium (Zr)	0.57 (85%)	1.84 (85%)	0.64 (85%)	0.92 (85%)	0.99 (85%)	0.88 (85%)

Table 4.9: Materials and their performance on indicators

4.2.4 Gold

There is clearly a bad coverage for gold. This is explained by the fact that gold is produced in many countries, so the production share for each country will be smaller. To obtain a better coverage, the top 10 producing countries will be taken into account, instead of only the top 5. The top 10 producing countries and corresponding coverage are: China (10,0%), Russia (9,6%), Australia (9,5%), Canada (6,8%), USA (5,7%), Mexico (3,8%), Kazakhstan (3,5%), South Africa (3,2%), Uzbekistan (3,2%), and Indonesia (3,1%).

All of these countries are included in Table 4.7, except for Uzbekistan. Uzbekistan scores on the social impact indicators as shown in Table 4.10.

Country	Child labour %	ASM miners %	HCB	WGI Rule of Law	WGI Corruption	HDI
Uzbekistan	18.0	0.06	3	-0.66	-0.95	0.740

Table 4.10: Performance indicators Uzbekistan

The resulting total score for gold is shown in Table 4.11.

Material	Child Labour	ASM	HCB	Rule of Law	Corruption	HDI
Gold (Au)	0.83 (49%)	1.75 (58%)	1.05 (58%)	1.57 (58%)	1.12 (58%)	0.50 (58%)

Table 4.11: Performance indicators Uzbekistan

To gain a valid result for Child Labour as well, the eleventh producer (Guinea, 3.0 %) is added. The result is shown in Table 4.12.

Material	Child Labour	ASM	HCB	Rule of Law	Corruption	HDI
Gold (Au)	0.95 (52%)	1.66 (61%)	1.05 (61%)	1.59 (61%)	1.17 (61%)	0.53 (61%)

Table 4.12: Performance indicators gold

4.2.5 Results

The two materials with the worst (highest) scores across all social impact categories are cobalt and tantalum. Next are tin, antimony and barium.

Materials with the lowest scores across all social impact categories are zirconium (hafnium) and lithium, lead and platinum.

Some materials have been excluded from the analysis, as their production is tied to being a by-product of other materials. As a reminder, an overview is given: arsenic is produced as a by-product of the extraction, production and purification of copper, lead, cobalt, and gold; gallium is produced as a by-product of aluminium production;

hafnium is produced as a by-product of zirconium production, and germanium and indium are produced as by-products of zinc production.

4.3 Discussion

4.3.1 Comparing to the Material Change Report

While the Material Change Report [9] focuses on specific industries in order to make a selection of materials, the analysis of the social impact of the different materials remains generally applicable. As such, it is insightful to compare the results of this work to those in the Material Change Report.

For the presence of violent conflict, control of corruption and rule of law, the same sources and a similar methodology have been used, so the results should be comparable. For control of corruption and rule of law, there is some variation as the scores for both WGI have increased significantly for China over the past eight years [100]. As China is an important producer of many materials, this has a positive impact on many materials. Additional differences in results can also be explained by the fluctuating WGIs for different countries. Concerning the presence of violent conflict, there is a significant difference in many materials. The general trend is that the Material Change Report reports a lower score for violent conflict than this work does. While the results do follow similar trends, i.e., countries with a lower score in the Material Change Report also have a lower score in this work, niobium is a clear exception.

The Material Change Report assigns a very high score to violent conflict (i.e., there is a lot of risk for this social impact category), while in this work, niobium has one of the lowest scores. This might be explained by the fact that a slightly different methodology is used: in the Material Change Report, the score is assigned based on the percentage of production happening in countries with a score of 4 or 5 in the Heidelberg Conflict Barometer. The similarity in both methodologies is that the score of a country is based on the highest score assigned to a region in the country. However, this work also looks at the countries with a score of 3. Additionally, there is a different way of assigning a final score: this work uses a weighted average of the scores of the top five producers, while the Material Change Report assigns a score based on the share of production happening in countries with a high conflict score. While these differences account for most of the fluctuations, it does not explain the vast difference in score for niobium. A hypothesis is that there has been a change in top producers, but the USGS Mineral Yearbook shows that Brazil was the main niobium producer in 2015 as well [115]. The trend of Brazil producing about 90% of niobium remains unchanged over the past ten years. Another hypothesis is that there is a different situation in terms of violent conflict in Brazil eight years ago. However, no such conflicts have been

found in the Heidelberg Conflict Barometer report [87], which also includes past conflicts. Finally, for other materials, the fluctuations can be explained by the fact that the Material Change Report takes into account additional producers, beyond the top 5 producing countries. However, for niobium, the full global production is covered by this work as well, so it remains unclear why there is this difference in results.

Two other social impact categories are discussed in both this work and the Material Change Report: child labour and ASM. For both social impact categories, a different methodology and different indicators are used. As such, it is not surprising that the results are different.

For child labour, this work utilizes the child labour rate per country. It is assumed that there is a correlation between the share of children working in general and the probability that there are also children working in mines. This is assumed after comparing countries with high rates of child labour and their presence on the USA's Department of Labor's Bureau of International Affairs (ILAB) "List of Goods Produced by Child Labor or Forced Labor" [70]. In the Material Change Report, materials are only included if they appear in this list. However, this list is deemed too limited, as outlined in subsection 3.3.1. As a result, there is a mismatch between the results in this work and the results in the Material Change Report: this work reports higher scores for child labour. However, the general trend of which countries score high and low remains the same.

For ASM, this uses the percentage of the population working in ASM, while the MCR considers sources per material instead of per country. A disadvantage of working with a percentage of the population is that differences in demographics are not taken into account. It would be better to express it as a percentage of the population of working age. Another disadvantage is that the ability to mine minerals in an artisanal way is heavily dependent on the nature of the ore. For some ores, it is not possible to mine them without heavy machinery, or the return of artisanal mining would be too low, resulting in the need for industrialised mining on a large scale. So, it is more precise to use mineral-based scores instead of country-based scores. However, it is not possible to find a database that provides such information for all the different materials in a comparable way. As such, it is decided to keep using the data per country. This results in generally higher scores for ASM per material compared to the results of the Material Change Report.

4.3.2 Conflict minerals

The two materials with the worst (highest) scores across all social impact categories are cobalt and tantalum. Next are tin, antimony, tungsten, bismuth and barium, which each have two or more social impact categories with a very high score. This is not surprising: there has been a lot of attention for so-called 3T conflict minerals. These are tin, tantalum and tungsten. The EU and USA have adopted laws in order to prevent supporting armed

groups in armed conflicts when trading those minerals: the Conflict Minerals Regulation in the EU [116] and the Dodd-Frank Act in the USA [117].

Also included in the conflict minerals is gold (so, the conflict materials are sometimes abbreviated to 3TG). Remarkably, both in this work and in the Material Change Report, gold performs rather well on the different social impact categories, including violent conflict. This is surprising, given the amount of legislation and research that exists on the mining of gold. A first reason for this extensive coverage could be that gold is mined in greater amounts than other metals, resulting in a bigger impact, even if there is a relatively low impact per category. However, this is not the case: the RMIS reports that in 2022, about 3 kt of primary gold was mined, which is very little compared to circa 397 Mt of bauxite, an ore mainly used for aluminium production [99].

The selection of 3TG as conflict minerals is coloured by the political context in which the legislation was created: it was created due to rising concerns among consumers, and then companies and policymakers, about the origin of the materials in their products. They were worried about the role of minerals tin, tantalum, tungsten, and gold in the DRC, as they were linked to human rights violations during their extraction and being used by armed groups to fund their operations [118]. As such, the inclusion of gold is relevant within that context, but it is too limiting to consider only these four conflict minerals when considering the social impact. Other due diligence frameworks, such as the OECD's, look to move away from only these conflict minerals and include all minerals, looking at risks, e.g., due to them being mined in CAHRAs [119]. As this work shows that other minerals may have a greater impact, it supports this approach as favourable over only focusing on conflict minerals.

4.3.3 Limitations and Recommendations

As discussed above, the database used provides information on primary production. This has two implications: not all data on primary producers provided by the RMIS refers to mining, and not all materials have available data to be included in this analysis. As this work focuses on the mining step, the first implication results in an analysis that might not be fully correct: it is possible that some of the production shares included are not exclusively through mining, rendering some of the social impact categories, e.g., ASM, less relevant to analyse.

As such, it might be more correct to base the analysis on the ores instead of on the end material. E.g. sphalerite is the main ore for zinc, and it is from this ore that germanium and indium are recovered as well. A more precise analysis would thus start from the materials, determine the most important ores for each material, and then repeat the previous analysis for the different ores instead of for the different materials. First of all, this ensures that the analysis considers the mining of ores. Secondly, this might allow for taking into account more detailed geographical data, as the presence of different ores is well-documented for several regions. Additionally, it

might allow the use of more precise data, e.g. ASM, which heavily depends on the specific ore.

Another limitation is that the analysis only takes into account the mining step. This is very limited, as many materials go through other production steps as well before entering the electronics supply chain. In order to obtain a more complete analysis, it is necessary to also include the other production steps in the analysis.

Additionally, the analysis happens at a country-by-country level. This gives the opportunity to use publicly available databases for the different indicators, and to keep a global overview of the mining of the different materials. However, a more nuanced analysis would also take into account variations at the local level. Especially in contexts with highly localised legislation or local crises, this might add relevant insights. Additionally, a complementary analysis for individual minerals would add nuance to the analysis. However, this is not within the scope of this work.

Finally, this work only reports a result per social impact category, rather than providing a single metric for social impact. While it would be possible to present the average or a weighted average of the different categories as this single metric, this is deemed incomplete: within the research carried out in the scope of this work, it has not become clear what a good weighting would look like. A more extensive analysis of the impact of each of the categories on the total social impact is necessary before such a single metric could be presented.

This analysis, based on materials and their mining at a country-by-country level, provides a reliable overview at a global level. It offers a method to efficiently and reliably evaluate the main materials used in PCBA fabrication. Moreover, it provides a good starting point for further, more extensive analysis, and a similar method may be applied to additional materials.

Chapter 5

Social impact and electronics industry

Now that the social impact of important materials has been assessed, the next step is to analyse the electronics industry consumption, i.e., the share of globally produced materials that are used within the electronics industry. This is an important metric as it gives an indication of the impact that is possible through changes in the electronics industry. Due to the scope definition of this work, this is not straightforward: while it is relevant for this work to take into account the electronics present in, for example, cars, the materials used for the casing of the car are not. So, the industry estimates that are available do not cater to the scope of this work, e.g. [9], which includes the industry consumption of the consumer electronics industry and the automotive industry. As such, the electronics industry consumption has to be estimated based on other sources.

Two sources are used: the Solutions for CRitical Raw materials - a European Expert Network (SCRREEN) criticality factsheets provided in the RMIS [99], and the Mineral Commodity Summaries and Minerals Yearbook chapters provided in the Minerals Yearbook published yearly by the USGS [120]. The SCRREEN criticality factsheets were created as part of an EU Horizon 20020 project and were published in the RMIS. For many materials, the factsheets provide information on their market and trading, demand, and supply. In the demand section, a section is devoted to uses and end-uses. Depending on the material, these provide a report on the global or EU uses and end-uses. The mineral commodity summaries and minerals yearbook chapters are published by the USGS. These contain information on the US production and uses, recycling, import sources, events, trends, and issues, etc. The information on the US uses is used if the SCRREEN factsheets only provide information on the EU uses.

It is not possible to copy the percentages reported in these sources to calculate the share of the global production used for electronics, as (1) the categories do not fully overlap with the scope of this work, as illustrated

above, and (2) each of the documents uses other classifications of the uses. For example, “high tech engineering”, “machinery”, and “mechanical engineering” are all used in different documents, but may partly overlap. To illustrate this, the uses of aluminium and beryllium are analysed as an example.

In the RMIS, the SCRREEN criticality factsheet [121] reports the following worldwide applications: 42% Mobility (transport and auto), 23% Construction, 17% Packaging, 12% High-Tech Engineering, and 6% Consumer Durables. High-tech Engineering only slightly overlaps with the scope of this work, as it contains “Manufacture of other electronic and electrical wires and cables” as only one of five sectors connected to this share of applications. Other related sectors, such as “Manufacture of tanks, reservoirs and containers of metal” are not within the scope of this work. There is no clarification on what share is used for these different sectors. Similarly, Consumer Durables covers, i.a.: cooking utensils, watches, electrical appliances, coins,... As such, it is not possible to extract a single percentage of the uses by the electronics industry.

For beryllium, the SCRREEN criticality factsheet [122] reports the applications in the EU as follows: 42% Electronic and telecommunications equipment, 17% Transport and Defence: Vehicle Electronics, 17% Transport and Defence: automobile components, and 10% Transport and Defence: aerospace components. It is clear that the first two categories are relevant to the scope of this work. However, the vehicle electronics category also includes ‘Manufacture of optical instruments and photographic equipment’. Clearly, not all production in this sector is relevant to our work. As such, it is not possible to consider $42\% + 17\% = 59\%$ of global consumption to be relevant to this work.

As this information only considers the use of beryllium within the European Union, the data is supplemented with data collected in the USGS Minerals Yearbook [120]. There, the following use within the USA is reported: 29% Consumer Electronics, 24% Aerospace and Defence, 17% Industrial Components, 9% Automotive Electronics, 8% Energy Applications, 2% Semiconductor Applications [123]. Clearly, this differs from the use in Europe, and it is hard to compare both, as a different categorization is used. However, it is still clear that a large part of beryllium consumption is relevant to the scope of this work.

When comparing the approach for beryllium and those on aluminium, two observations can be made. First, for beryllium, an additional source is needed to gain insights beyond the EU. While still not complete, as both sources only cover the USA and the EU, adding the USA data provides an additional insight which is necessary to evaluate the use at a global level. Second, qualitatively, it is clear that the electronics industry consumption is greater in beryllium: there are more applications that are relevant to the scope of this work, and electronics are specifically mentioned a few times. So, the share of global production that is used by the electronics industry is greater for beryllium than it is for aluminium.

In the remainder, a similar analysis will be made for the rest of the materials. First, it is checked whether there is global information available in the SCRREEN factsheets for the applications of the materials. If not, supplementary information from the USA will be considered as well. Secondly, the most important uses of each material are assessed, and to what extent these are relevant to the scope of this work. Based on these results, a qualitative assessment is made.

In Table 5.1, the uses are reported for the different materials. Uses relevant to this work are highlighted. The colour indicates how relevant the category is, or to what extent the relevant scope is included in the term: **slight overlap** - **great overlap** - **full overlap**. The assignment happens qualitatively. Terms that are not highlighted are not considered to be relevant to our scope. If the SCRREEN factsheet provides global information, the US-specific data is not consulted. If it only provides EU data, the US-specific data is added in the third column.

Material	Uses reported by SCRREEN (global/EU)	Uses reported by USGS (US)
Aluminium (Al)	42% Mobility (transport and auto), 23% Construction, 17% Packaging, 12% High-Tech Engineering, and 6% Consumer Durables [121]	
Antimony (Sb)	43% Flame Retardants, 32% Lead-acid Batteries, 14% Lead alloys, 6% Plastics, 5% Glass and Ceramics [124]	49% Flame Retardants, 40% Antimonial Lead and Ammunition, and 11% Nonmetal Products, including Ceramics, Glass, and Rubber Products [125]
Arsenic (As)	70% Zinc Production, 18% Glassmaking, 7% Chemicals, and 5% Alloys [113]	> 80% Production of Herbicides, Insecticides, and Wood Preservatives, and <20% Metallurgical and Semiconductor Applications [126]
Barium (Ba) ¹	60% Weighting Agent in Oil and Gas Well Drilling, 30% Filler in Rubbers, Plastics, Paints, and Paper, and 10% Chemicals [127]	>90% Weighting Agent in Fluids used for Drilling of Oil and Natural Gas Wells, <10% Filler, Extender, or Weighting Agent in Paints, Plastics, and Rubbers [128]
Beryllium (Be)	23% Industrial Components, 17% Aerospace and Defence, 17% Automotive, 12% Consumer Electronics, 11% Telecommunication Infrastructure, 5% Energy, 1% Semiconductor, and 14% Other [122]	18% Consumer Electronics, 24% Aerospace and Defence, 17% Industrial Components, 9% Automotive Electronics, 8% Energy, 1% Semiconductor, and 11% Other [123]
Bismuth (Bi)	84% Chemicals, 9% Low-melting Alloys, and 7% Metallurgical Additives [129]	No quantification available; Cosmetic, Industrial, Laboratory, and Pharmaceutical applications mentioned as main use. Use in solder is mentioned as minor use [130]

¹Information on use of baryte, the main ore for barium

Material	Uses reported by SCREEN (global/EU)	Uses reported by USGS (US)
Boron (B)	55% Glass, 17% Frits and Ceramics, 15% Fertilisers, 4% Chemical Manufacture, 4% Construction Materials, and 4% Metals [131]	No quantification available; Glass and Ceramics industries as main use, Semiconductors mentioned as minor use [132]
Chromium (Cr)	74% Products made of Stainless Steel, 19% Products made of Alloy Steel, 3% Casting moulds, 3% Products made of Chromium Chemicals , and 1% Refractory Bricks and Mortars [133]	No quantification available; Stainless Steel and Heat-resisting Steel are mentioned as the main uses. [134]
Cobalt (Co)	57% Batteries, 6% Pigments, 5% Catalysts, 4% Magnets , 13% Nickel-based Alloys , 8% Tool Material, 2% Soaps and Dryers, and 5% Other [135]	
Copper (Cu)	20.5% Electrical Power, 13.5% Power Utility, 2.6% Telecommunications , 11.6% Industry , 8% Automotive, 4.4% Other Transport, 8.9% Consumer and General Products , 8.1% Cooling, 5.3% Electronic , 0.8% Communications , and 16% Diverse [136]	
Gallium (Ga)	70% Integrated Circuits , 25% Lightning, and 5% CIGS Solar Cells [111]	73% Integrated Circuits , and 26% Opto-electronic devices [137]
Germanium (Ge)	34% Optical Fibres, 22% Infrared Optics, 17% Electronic and solar , 21% Polymerization Catalysts, and 6% Other [109]	
Gold (Au)	86.4% Jewellery, 11.2% Electronics , 1.9% Other Industrial, and 0.5% Dentistry ² [138]	
Hafnium (Hf)	61% Superalloys , 15% Plasma cutting tips, 11% Nuclear control rods, 7% catalyst precursors, 3% Oxide for Optical Applications, and 3% Semiconductors [112]	
Indium (In)	60% Flat Panel Displays, 11% Solders , 9% PV Cells, 7% Thermal Interface Material, 6% Batteries, 4% Alloys/Compounds , and 3% Semiconductors and LEDs [110]	No quantification; flat-panel displays mentioned as major use, Alloys and Solders , Compounds , Electrical Components and Semiconductors , and Research mentioned as minor use. [139]
Iron (Fe)	38% Construction, 16% Automotive, 15% Mechanical Engineering, 14% Metalware, 10% Tubes, 2% Domestic Appliances, 2% Transport, and 3% Other ³ [140]	98% Steel Industry, 2% Nonsteel end uses [141]

²Non-monetary uses³Data on use of Iron and Steel

Material	Uses reported by SCRREEN (global/EU)	Uses reported by USGS (US)
Lanthanum (La)	79% Catalysts (FCC), 12% Metallurgical, 3% Polishing Powders, 1% Batteries, 1% Glass, and 4% Others [99]	No data available
Lead (Pb)	84% Batteries, 6% Rolled and Extruded Products, 4% Compounds and Pigments, 4% Shots and Ammunition, 1% Alloys and Solder, and 1% Cable Sheathing [142]	67% Lead-acid batteries, no further quantification available [143]
Lithium (Li)	71% Batteries, 14% Ceramics and Glass, 4% Lubricating Greases, 2% Polymer Production, 2% Continuous Casting Mold Flux Powders, 1% Air Treatment, and 6% Other [144]	
Manganese (Mn)	43% Building and Construction, 20% Transportation, 17% Engineering, 14% Metalware, 2% Domestic Appliances, 2% Batteries, and 2% Miscellaneous [145]	No quantification; production of Pig Iron mentioned as major use, production of animal feed, brick colourant, dry cell batteries, and fertilisers as minor use. [146]
Molybdenum (Mo)	39% Engineering Steels, 24% Stainless Steels, 13% Chemicals, 8% Foundries, 8% Tool Steels, 5% Mo-Metals, 3% Nickel Alloys [147]	
Nickel (Ni)	72% Stainless Steel, 7% Alloy Steel and Casting, 7% Plating, 7% Batteries, 6% Ni-based and Cu-based alloys, and 1% Other [148]	
Niobium (Nb)	47% Construction (steel), 24% Automotive (steel), 17% Oil and Gas, 10% Stainless Steel, and 2% Special Steel [149]	77% Steel, and 23% Superalloys [150]
Palladium (Pd)	86% Autocatalyst, 6% Electronics, 5% (Electro)chemical and Petroleum, 2% Medical, and 1% Jewellery; calculated based on information in [151]	
Phosphorus (P)	No data available	95% Fertilisers and Animal Feed, and 5% Industrial Applications [114] ⁴
Platinum (Pt)	39% Autocatalyst, 31% Jewellery, 15% (Electro)chemical and Petroleum, 7% Glass, 5% Electronics, and 3% Medical; calculated based on information in [151]	
Rhodium (Rh)	60% Autocatalyst, 39% (Electro)chemical and Petroleum, and 1% Glass; calculated based on information in [151]	
Ruthenium (Ru)	55% (Electro)chemical and Petroleum, and 45% Electronics; calculated based on information in [151]	

⁴Data on use of phosphate rock, the main ore for phosphorus

Material	Uses reported by SCRREEN (global/EU)	Uses reported by USGS (US)
Silver (Ag)	43% Electronics, 24% Jewellery, 15% Photovoltaics, 6% Silverware, 6% Brazing Alloys and Solder, 4% Photography, and 2% Other Industrial[152]	
Tantalum (Ta)	36% Capacitors, 24% Superalloys, 11% Sputtering Targets, 12% Mill Products, 9% Carbides, and 8% Chemicals	No quantification; Tantalum Alloys, Capacitors, Carbides, Compounds, and Tantalum Metal mentioned as the major uses.
Tin (Sn)	48% Solders, 17% Chemicals, 12% Tinplate, 7% Lead Acid Batteries, 7% Copper Alloys, and 9% Other [153]	
Titanium (Ti)	45% Civil Aerospace, 40% Industrial Equipment, 9% Military Applications, and 6% Consumer Goods and Other [154]	
Tungsten (W)	33% Transport, 22% Mining and Construction, 14% Industrial uses 8% Consumer Durables, 6% Energy, 6% Defence, and 11% Other [154]	
Vanadium (V)	64% High-strength Low-alloy Steels, 21% Special Steel, 5% Chemicals and Battery Oxides, 4% Stainless Steel, 3% Energy Storage, and 3% Superalloys for High-end Uses [155]	
Zinc (Zn)	58% Galvanizing, 13% Zinc Alloy, 13% Brass and Bronze, 8% Chemical Compounds, 5% Rolled Zinc, and 3% Other [156]	
Zirconium (Zr)	43% Ceramics, 15% Refractories, 15% Foundry, 12% Chemicals, 3% Pigments, 2% Superalloys, and 10% Other [157]	No quantification; Ceramics mentioned as major use, Foundry Sand, Refractories, and Zirconium Chemicals mentioned as minor use. [158]

Table 5.1: Materials and their uses

When taking into account the share of the different applications (in %) and their relevance to the scope of this work (indicated by the highlight colour), the consumption of the global production by the electronics industry is considered to be:

- Very high: beryllium, copper, gallium, ruthenium, silver, tantalum;
- High: aluminium, indium, palladium, platinum, tin;
- Low: antimony, arsenic, bismuth, cobalt, germanium, gold, rhodium, zinc, zirconium;
- Very low: barium, boron, chromium, iron, lanthanum, lead, lithium, manganese, molybdenum, phosphorus, titanium, tungsten, vanadium.

Chapter 6

Detailed analysis materials

In this chapter, a deeper analysis will be made of a selection of materials. For each of these materials, a more detailed overview of the social impact will be given, and alternative materials for the main applications will be discussed, taking into account technological properties and cost.

To make a selection of materials, the two materials with the highest social impact are first selected: tantalum and cobalt. Then, an additional material is selected by considering the materials with at least one pink social impact category and comparing these to the materials for which there is a high consumption by the electronics industry, as for these materials, a change within the electronics industry has the biggest impact. The materials with at least one pink social impact category are: aluminium, antimony, barium, beryllium, bismuth, boron, chromium, copper, iron, nickel, rhodium, ruthenium, silver, tin, tungsten, vanadium, and zirconium. Of this selection, beryllium, copper, ruthenium, and silver have the greatest electronics industry consumption. Finally, the material with the greatest social impact is selected for further analysis: silver. So, in this chapter, the following materials will be analysed: cobalt, tantalum, and silver.

6.1 Cobalt

6.1.1 Social Impact

Cobalt has a high social impact. Its top five producing countries are: the Democratic Republic of the Congo (69.2%), Russia (6.0%), Australia (3.9%), Canada (2.9%), and Cuba (2.8%) [99]. As the DRC produces the majority of Cobalt, this discussion will focus on the situation in the DRC only.

Cobalt production in the DRC is linked to the copper production, as its prevalence is mostly within copper-

cobalt ores of varying composition. These ores are mostly found in the southern part of the DRC, in the so-called Copperbelt [91]. Due to the nature of these ores, they are extracted mostly through industrial mining. Most of the mines are controlled by foreign corporations through mining concessions. However, there is a parallel circuit of artisanal miners, often operating at the periphery of these industrial concessioned areas. An estimated 15-30% of cobalt is produced by artisanal miners. A significant part of this artisanal mined cobalt is sourced by the industrial mining companies and mixed into their supply chain [6]. As such, the risks associated with ASM are still relevant to cobalt. Especially so, because there is a great risk of conflicts between artisanal and industrial miners, which is known to pose risks to the socioeconomic reality of surrounding communities [76]. Take, for example, the tragic collapse of a bridge in a mine in Lualaba in November 2025, allegedly caused by a conflict between soldiers protecting the borders of the concession and artisanal miners. This collapse resulted in more than 30 casualties [79].

Additionally, the artisanal mining of cobalt has been linked to widespread child labour. For example, in 2012, it was estimated by UNICEF that in southern Katanga, 40 000 children were working in the mines, forming about one-third of the total number of workers. Another report estimates that there are 200 000 children active in ASM in the DRC [159]. As such, child labour is considered to be a major concern in the mining of cobalt.

Violent conflict is of less concern in the mining of cobalt. The main conflicts in the DRC are in the Great Lakes Region, in Eastern DRC. This is reflected in the CAHRAs: the regions of Tanganyika, Haut-Lomami, Lualaba, and Haut-Katanga, where most of the cobalt is mined, are listed as high-risk and not as conflict-affected [86].

The widespread issues in the DRC with Rule of Law and Control of Corruption also remain an issue in cobalt mining. Especially, the conflicts between industrial and artisanal mining are often a result of conflicts of interest among local politicians. Additionally, there are many questions about the large-scale concession deals for these copper-cobalt mines with multinationals. As a prime example, the Sicomines deal has been critiqued nationally and internationally due to its lack of transparency and return for the Congolese people [118].

6.1.2 Applications within Electronics and possible substitutes

6.1.2.1 Inductor Core

Most inductors consist of a magnetic core around which a conductive wire is wound. There are different types of cores. One of these types is Amorphous Magnetic Materials (AMM).

In inductors, a magnetic core is added in order to increase the permeability, resulting in an increased inductance. There are two main loss mechanisms when using magnetic cores: hysteresis losses and eddy current losses.

Hysteresis losses happen due to hysteresis: the asymmetrical “charging” and “discharging” will result in losses proportional to the area created by the hysteresis curves. Eddy currents are caused when, during use with AC, AC voltages are induced in the core material itself, resulting in power dissipation through the core [160].

So, the different core materials are selected based on how they can help to mitigate these losses. In amorphous magnetic materials, the eddy current losses are limited because the material consists of magnetic powder granules with “distributed air gaps”. Additionally, amorphous magnetic materials are characterised by a narrow hysteresis curve, resulting in low hysteresis losses as well [35]. A disadvantage is the high cost [161] and the low saturation magnetization and losses that seriously increase at high excitation magnetic fields [162].

While these materials are mostly used within electrical power systems, which are not necessarily within the scope of this work, there are also applications within electronics and sensors [163].

There are three possible main metals for ferromagnetic AMMs: they typically contain 80% iron, nickel and/or cobalt. The rest of the alloy consists of 20% metalloid additions such as phosphorus, silicon, aluminium, carbon and boron. One advantage of Cobalt-based AMMs is that they show a low magnetostriction, deformation during the magnetization process [162]. Additionally, using cobalt is required to reach a high saturation induction. As cobalt is a very expensive component, alternatives without cobalt (with a lower saturation induction) have been created, e.g. METGLAS 2650SA1 [163].

6.1.2.2 Silicidation Process

The silicidation process is the first step in forming the metal-semiconductor contacts after fabricating the source, drain, and gate regions on the substrate. This process is used to increase conductance at targeted sites, i.e., source, drain and gate. As silicide has a high conductivity, it creates a low-resistance connection with the contacts. This step forms the last step of fabricating the FEOL and allows connection to the BEOL [37].

During the silicidation process, a layer of silicide is formed. Instead of depositing a layer of silicide by sputtering, CVD, or other methods, a layer of silicide is formed after depositing a transition metal on the silicon and the subsequent chemical reaction with the silicon substrate. Common metals to use are: Pt, Ti, Co, W, Mo, Ta, and Ni [12], [37].

The most popular silicides to use for this purpose are titanium silicide (TiSi_2), tungsten silicide (WSi_2), cobalt silicide (CoSi_2), and nickel silicide (NiSi_2) [164]. Based on the information provided in [37, Table 11.4], the silicides resulting in the lowest resistivity are TiSi_2 , CoSi_2 , and NiSi . A disadvantage of NiSi is that it is only stable up to 650°C , which heavily limits the fabrication options for the remainder of the BEOL. Between TiSi_2 and CoSi_2 ,

research shows that the cobalt silicidation process is faster, and thus cheaper, and results in a layer with better electrical properties [164]. So, titanium silicide could be a viable substitute for cobalt silicide; however, this is a more expensive option.

6.1.2.3 Metal Packaging (in Kovar)

Packaging is the hermetic enclosure of the chip and the interface to electrical testing and the next assembly level [40]. Large contributors of metals in electronic packaging are the lead frame, complete metal housing and metal lids for thermal interfacing. Kovar is used as a lead frame material and for metal housing. Depending on the application, the following factors might be of importance when picking a material: mass, price, thermal conductivity, and (mismatch of) coefficient of thermal expansion [165].

Mass may be important if the application has weight restrictions. Thermal conductivity may be important if heat management is a concern. The coefficient of thermal expansion may be important in applications where there are a lot of temperature fluctuations. The mismatch of coefficients of thermal expansion is important in applications where a lot of different materials are combined in the packaging.

One of the metals which is often used for packaging is Kovar. Kovar is an alloy of iron (53.4% minimum), nickel (29%), cobalt (17%), silicium (0.10%), manganese (0.30%), and carbon (0.02% maximum) [166]. However, there are other options to use for the packaging as well: molybdenum, tungsten, aluminium,... Common choices are selected from the literature, and their properties are listed in Table 6.1.

The properties of molybdenum, copper-tungsten 10/90, tungsten, aluminium, copper, gold and Kovar, selected from [40] and [165], are shown in Table 6.1. In order to calculate the price, an estimation is made of the 6-month average available at 28/04/2026. If no sources with price trends are found, other sources are collected: daily price trends, price trend reports, and, as a final resort, prices made available online by manufacturers.

Substitutes of Kovar depend entirely on the specific application. In any case, there will be a trade-off between the different properties. For example, a material with similar thermal properties is aluminium oxide, which has a thermal conductivity of 15-33 W/(m·K) and a CTE of $4.3\text{-}7.4 \cdot 10^{-6}/\text{K}$. However, aluminium oxide is a ceramic, which results in the loss of electromagnetic shielding. If the electrical properties are more important, other metals might be considered. For example, gold-plated aluminium is suggested as a more lightweight alternative to Kovar in [165].

Material	Price (USD/kg)	Thermal Conductivity κ (W/(m·K))	Linear CTE ($10^{-6}/K$)	Density (g/cm ³)
Molybdenum	73 [167]	138 [40]	3.0-5.5[40]	10.2 [168]
Copper-Tungsten 10/90	125 [169]	209 [40]	6.0[40]	0.1·8.96+0.9·19.3 = 18.26
Tungsten	275 [170]	174-177[40]	4.5[40]	19.3[171]
Aluminium	3.2[172]	210[165]	24[165]	2.70[173]
Copper	12.50 [174]	398[165]	16.5[165]	8.96[175]
Gold	150 000 [176]	315[165]	14.4[165]	19.3[177]
Kovar	36 [178]	16 [165]	5.9[165]	8.36[166]

Table 6.1: Popular metals and their properties. Data on thermal properties from [40, Table 12-9][165, Table I].

6.2 Tantalum

6.2.1 Social Impact

Tantalum has a high social impact. Its top five producing countries are: the Democratic Republic of the Congo (42%), Brazil (19%), Rwanda (14%), Nigeria (6%), and China (4%) [99]. The social impact of the DRC and Brazil will be discussed in detail, covering around 60% of the global production.

In the Democratic Republic of the Congo, tantalum mostly occurs within the coltan ore, which contains niobium and tantalum. These ores are mainly found in the eastern part of the DRC, in the Congolese part of the Great Lakes Region. As the ore is mostly found in surface alluvial deposits, it is rather easy to mine with only a pick and a shovel. As such, it is mostly mined through artisanal mining (ASM) [179]. The ore is often mined together with tin, as its prevalence overlaps with the prevalence of the cassiterite ore.

Eastern Congo has been plagued by violent conflict over the past decades. In recent years, this conflict has been centred around the Kivu region. The conflict stems from the Second Congo War, which officially lasted from 1998 to 2003, but never completely ended. Ever since then, armed groups have been fighting in the region to gain control, with detrimental consequences for the local population. What initially started as an ethnic conflict now also often involves the control of mining sites of gold, tantalum, and other valuable minerals. As the main rebel groups are backed by either the DRC or Rwanda, the situation is very complex [118].

It is estimated that 64% of global tantalum production is by ASM. The DRC is responsible for a disproportionate share of this number: the ASM sector is widespread in the DRC. It is estimated that it employs 80% of the 2.5

million workers directly employed in the DRC's mining industry, and that an estimated 16% of the population is dependent on ASM for their livelihood [180][6].

In combination with the widespread presence of violent conflict, ASM poses several challenges. First, there is the concern for the safety of the workers. As outlined in subsubsection 3.3.2.2, active battle seldom centres around mining sites. However, the control of mines by non-state parties or security forces comes with risks of extortion, illegal taxation, forced labour, and sexual violence [65]. Besides, the conflict creates a "crisis economy", where trading routes constantly change, following the dynamics of the conflict [75]. Due to the nature of the conflict, it facilitates smuggling, involving semi-official trade routes to neighbouring countries, Rwanda, Uganda and Burundi, where they then end up in the legal global market [181]. The informal nature of these trade routes makes it difficult to trace back all involved parties and to enforce due diligence.

In line with the common presence of child labour in ASM [159], the ASM of coltan is also linked to child labour. Due to the presence of violent conflict in the region, these children face additional risks such as recruitment by armed groups [181].

The widespread issues in the DRC with Rule of Law and Control of Corruption also remain an issue in coltan mining. In the context of the conflict, state security forces are also reported to take part in illegal road blocks, illegal taxation, extortion, etc., contributing to the state of crisis in the region. Additionally, there is a common issue of corrupt state officials throughout the supply chain. Examples of such corruption are illegal taxation or extending illegal "concessions". There are even reports of state officials obstructing the rollout of responsible mining initiatives[181].

In Brazil, marginal production levels of tantalum come from ASM, despite the country having an estimated 861 000 people working in ASM [182]. Most of the mining happens in large-scale mines, often by multinational companies [183]. Still, in general, several risks are linked to the ASM sector in Brazil: there are growing concerns of modern slavery taking place in the sector [184].

In terms of child labour, Brazil has made much progress over the past decades, resulting in a rather low child labour rate of 2%, following the ILO's classification [69], and 4.3% following Brazil's legislative classification. The number in Brazil is higher, for example, because Brazil allows no labour until 16, while the ILO guidelines allow up to 14 hours a week for 14- 15-year-olds. While no data has been found on what share of this percentage is active in mining, it is suggested that it is one of the smaller sectors[185].

Violent conflict is not a major concern in Brazil. In the Heidelberg conflict barometer, Brazil is assigned a conflict intensity of 3 [87], referring to drug violence and political unrest. It is unclear how these ongoing

conflicts impact the mining sector.

In terms of Rule of Law and Control of Corruption, Brazil scores below average. This has implications for the mining industry. For example, two major environmental tragedies happened in 2015 and 2019 at Vale S.A.'s mining sites, resulting in more than 350 dead and more than 600 injured. It is suggested that these incidents are a consequence of inadequate environmental licensing and surveillance by the state, possibly due to extensive lobbying by Vale S.A. [186].

In conclusion, the social impact of the mining of tantalum is very high in the DRC due to the entanglement with the violent conflict that has been ongoing over the past decades. The social impact of the mining of tantalum in Brazil is lower, but still considerable due to the concerns over the rule of law and control of corruption.

6.2.2 Applications within Electronics and Possible Substitutes

6.2.2.1 Dielectric in Electrolytic Capacitors

(Electrolytic) Capacitors are the most common application of tantalum [99]. Electrolytic capacitors consist of a cathode and an anode. Between the cathode and the anode, there is an electrolyte for conduction. This electrolyte is often considered to be an extension of the cathode. An oxide layer on the anode metal acts as the dielectric between the two plates. As such, the capacitor has a polarity. This working principle is shown in Figure 6.1. The different types of electrolytic capacitors are divided based on the oxides which act as a dielectric, which are formed on the metal anode. The most common types are aluminium, tantalum, or niobium. Aluminium and tantalum are the most used types because they can be made very thin, resulting in a high capacitance [187].

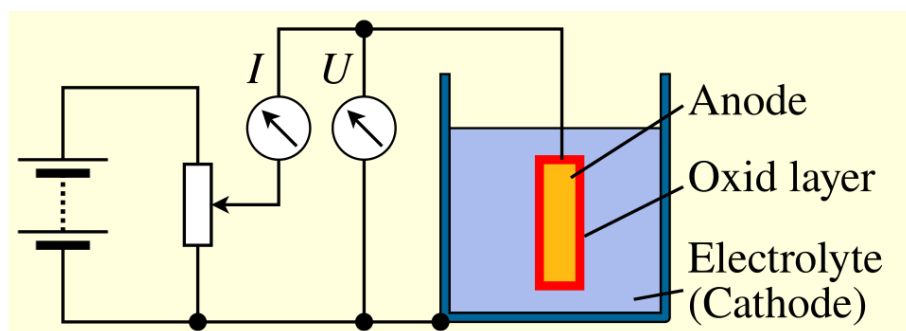


Figure 6.1: Working principle of an electrolytic capacitor. Taken from [188]

Electrolytic capacitors are popular to use because they have a high volumetric capacitance, allowing for smaller sizes. The aluminium electrolytic capacitor (AEC) is the most widely used variant. It is cheap to produce, as it

is made from cheaper materials and manufacturing processes, while still having a wide range of operating temperatures, good stability and a long service life [189].

Tantalum electrolytic capacitors (TECs) have better stability due to their high corrosion resistance, a wider operating temperature range and a longer service life than AECs. Some types of TECs are no longer in use. For example, the expensive wet tantalum foil style capacitor is often replaced with AECs with a comparable capacitance per unit, and silver can cathodes have been phased out due to their high risk of short circuits if the capacitor is not correctly polarised [187]. However, TECs with a wet sintered tantalum electrolytic, i.e. H_2SO_4 , are still popular to use. Capacitors with this electrolyte allow a high energy density, and high currents may be obtained without creating as much heat as in AECs [189]. They are thus popular to use in high-energy, high-power applications [187].

Niobium electrolytic capacitors were widely optimised at the start of the 2000s in response to a price surge of tantalum. As niobium has a more widespread availability, its prices are more affordable. Niobium capacitors offer advantages similar to those of tantalum: they show similar chemical properties, resulting in very stable devices, and it has an even greater dielectric constant, allowing smaller devices. However, the maximum temperature operation is more limited, and it only allows a low voltage. As such, niobium electrolytic capacitors do not form a good alternative for tantalum electrolytic capacitors in high-energy, high-power applications [189].

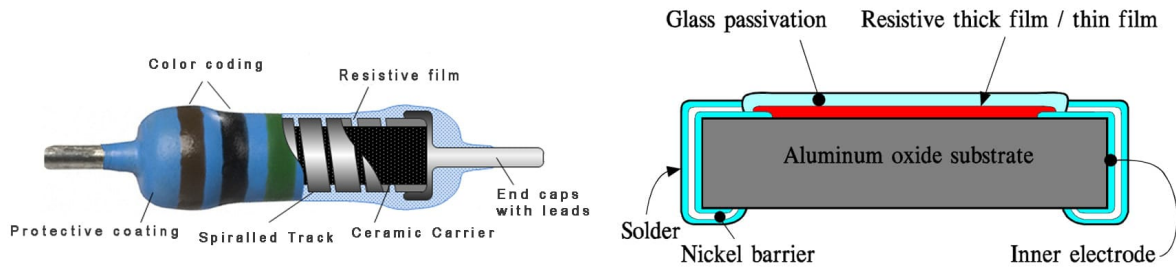
An overview of the operating properties of the different types of electrolytic capacitors is given in Table 6.2

Dielectric	Electrolyte	Capacitance (μF)	Maximum temperature ($^{\circ}\text{C}$)	Operating Voltage (V)
Alumina oxide (Al_2O_3)	GBL, DMF, DMA	$0.1 - 10^6$	150	550
	Borax, glycol	$0.1 - 10^6$	105	630
	Water based	$1 - 20\,000$	105	100
	Solid, Polymer	$10 - 2000$	100	25
	Hybrid polymer solid and non-solid	$6 - 10^3$	125	125
Tantalum oxide (Ta_2O_5)	Sulfuric acid	0.1 to $20\,000$	200	650
	Solid, Manganese dioxide	$0.1 - 3000$	150	120
	Solid, Polymer	$5 \cdot 10^3$	125	10
Niobium oxide (Nb_2O_5)	Solid, Manganese dioxide	$1 - 10^3$	125	10
	Solid, Polymer	$5 - 500$	125	16

Table 6.2: Operating properties of the different types of electrolytic capacitors, taken from [189]

6.2.2.2 Film Resistors

Film resistors are a type of resistor constructed around a ceramic rod or substrate. An example of a typical through-hole and surface-mount film resistor is shown in Figure 6.2. The nature of this film results in the division of types of film resistors between metal film (thin film), metal foil, metal glaze (thick film), metal oxide, carbon film, carbon composition, and conductive plastic. The most dominant type is the metal film or thin film resistor. Thin film resistors are popular due to their high precision and thermal stability [190].



(a) A typical through-hole film resistor. Taken from [190]. (b) A typical surface-mount film resistor. Taken from [191].

Figure 6.2: Typical film resistors

The most common film alloy is NiCr. It is popular to use as it allows to easily produce resistors with a low temperature coefficient of resistance (TCR). Resistors with a low TCR are more stable to use in environments with varying temperatures. However, the downside of NiCr is that it corrodes easily in humid environments, reducing the stability of the component. This is problematic for applications with a humid environment where stability is important [192][193].

For these applications, tantalum nitride (Ta_2N) is often used, possibly with additives of aluminium, silicon, or titanium. As tantalum is highly corrosion-resistant, it has high reliability in a humid environment [192]. It is also popular to use in audio applications due to its low noise characteristic [190]. However, when not strictly needed, tantalum is not used due to two factors. First, the fabrication process for tantalum nitride thin film resistors is expensive [193]. Additionally, it is difficult to fabricate tantalum nitride thin film resistors with a TCR as low as in nichrome thin film resistors. As such, it has a lower reliability in applications with fluctuating temperatures[192]. Due to its specific set of properties and due to the fact that its use is already limited, there is no strong alternative to tantalum alloys for those applications.

6.2.2.3 Diffusion barrier

During the fabrication process of ICs, diffusion barriers play an important role. These layers are deposited with the goal of preventing diffusion of one layer into the other, without causing undesirable electrical behaviour.

This is a concern, especially during the BEOL processing step: the diffusion of conducting particles into the FEOL would be detrimental to the operation of the IC. This principle is shown in Figure 6.3. As is visible in the figure, the thickness of the junction plays a role as well: the narrower it is, the more sensitive it is to diffusion.

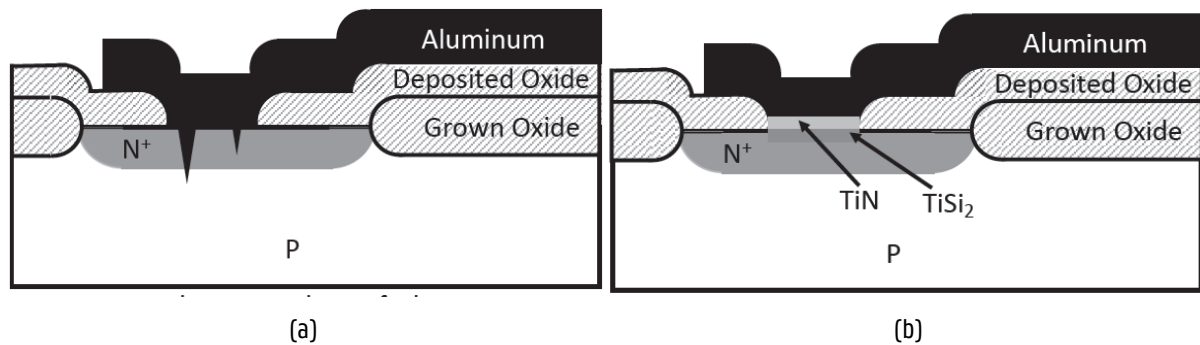


Figure 6.3: Aluminium-silicon contact. In (a), there is no barrier layer, and there are spikes due to the diffusion of aluminium, resulting in malfunction. In (b), there is a titanium barrier layer, which prevents diffusion. This results in no spikes and a correctly functioning device. Taken from [37].

During the fabrication of new contacts, a barrier layer needs to be deposited between the underlying silicon and the contact metal. This layer has to meet the following requirements: (1) be a barrier to chemical diffusion at processing temperatures, (2) be thermally stable, (3) have a CTE that is similar to that of the underlying or the upper layer, to reduce stress, (4) adhere well to the underlying and upper layers, and (5) have a good electrical conductivity and low contact resistance to both underlying and upper layers [37].

So, clearly, the choice of the barrier material depends on the underlying and upper layers.

During contact hole formation of, e.g., a Si/Al contact or a Si/W contact, a TiSi_2/TiN or Ti/TiN is widely used. The TiSi_2 or Ti is added first as a contact layer, and then the TiN is added as a barrier layer. The contact layer is added in order to have good adhesion and low contact resistance. The TiN is added as a barrier layer, as there is very slow diffusion through it. As such, it is practically impermeable to silicon and most other species.

Similarly, barrier layers are deposited during the BEOL fabrication process to prevent copper from diffusing into surrounding dielectric layers. Ta/TaN is popular to use for this purpose, as it has very good diffusion blocking properties and has a high thermal and chemical stability. Additionally, it has good adhesion to copper and the various types of dielectric materials. A disadvantage is that the layer has a rather high resistivity [194].

In order to address this disadvantage, several materials have been researched as alternative barrier layers. For example, W-based and Ti-based barriers were researched [195]. Both present challenges. For W-based barriers, it is difficult to reach high adhesion between the barrier and the Cu, and it is difficult to reach a sufficient level of thermal stability. Ti-based barriers were difficult to integrate due to, i.e., corrosion during CMP and high resistivity [196].

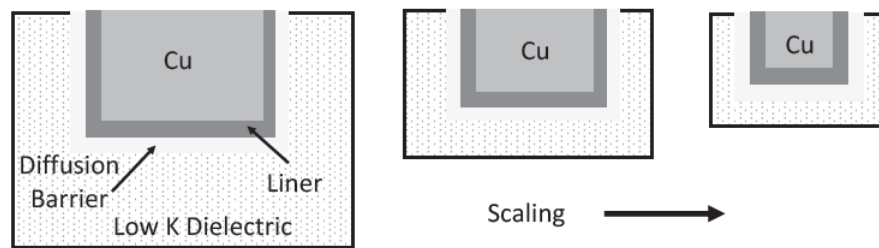


Figure 6.4: Downsizing of interconnects. Size of adhesion and barrier layers stays constant. Taken from [37, fig. 11.41]

The barrier layer presents a challenge when downsizing: the layer needs to be of a certain thickness to prevent diffusion. As such, as the chip sizes shrink, the barrier layer needs to stay the same thickness; this is illustrated in Figure 6.4. This results in problems when downsizing. To mitigate these problems, alternative interconnect materials are researched, such as ruthenium and cobalt, which do not need barrier layers due to their low diffusivities [37]. Alternative barrier materials are also being researched, such as MoS_2 [197].

6.3 Silver

6.3.1 Social Impact

Silver has a rather high social impact. The top five producers of silver are: Mexico (23.6%), China (13.5%), Peru (12.8%), Chile (5.3%), and Australia (5.1%). Considering the indicators for each of these countries, two stand out: Mexico has a high level of active violence and low rule of law. Peru has a high child labour rate. These two will be discussed below.

Mexico has a high level of active violence. Inter-cartel violence has reached an intensity of 4 ('limited war') in the Heidelberg Conflict Barometer [87]. This violence directly impacts the safety of mining workers. For example, in January 2026, 10 workers of the mining company Vizsla Silver were kidnapped [198]. It is estimated that from 2006 to 2019, 42% of the reported violent conflicts in Mexico were related to the mining industry [199]. Beyond the active conflicts, some resource-rich areas have been under the territorial control of criminal organisations. In these regions, they extort companies and ASM miners, e.g. by asking for protection money, adding to safety concerns. Due to the surge in silver and gold prices, this has been on the rise in recent years [200]. Violence is widespread and intertwined with the mining sector, heavily contributing to the social impact of the mining sector [201]. This widespread violence adds to the lowly perceived rule of law, as many questions are raised about the government's strategy to address the problem [200].

In Peru, the child labour rate is particularly high, at 16% [67]. Mining is one of the sectors most affected by

child labour. This mostly takes place in ASM operations, where there is a lack of government presence. Beyond the occupational risks these children face, there are also reports of child trafficking and the use of children for commercial sexual exploitation in the margins of these mining operations [202]. Reports show that these risks are mostly centred around the production of gold, e.g., this report on the Mollehuaca mines reported an annual production of 750 kg of gold (worth \$7 million), compared to an annual production of 144 kg of silver (worth \$ 24 000) [202]. Still, this combination of child labour, ASM, and reports of low government control is considered to have a big social impact.

6.3.2 Applications within Electronics and Possible Substitutes

6.3.2.1 Surface finish PCB and Solder

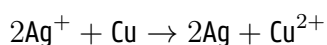
The purpose of the surface finish is to provide a protective coating to the exposed copper circuitry in order to preserve solderability. Silver is used in two common surface finishing techniques: Hot Air Solder Levelling (HASL) and immersion silver [203].

HASL is widely used. Traditionally, it used a tin-lead solder alloy. However, as outlined in section 2.5, the use of lead in EEE has been banned under the RoHS directive. This resulted in the search for lead-free solder. One of the most prominent lead-free solder alloys is SAC (Sn-Ag-Cu). Prominent types of SAC are: SAC305 (96.5%Sn-3.0%Ag-0.5%Cu) and SAC387 (95.5%Sn-3.8%Ag-0.7%Cu) [204]. These alloys are near-eutectic, robust in thermal cycling, have a good drop shock resistance, etc. [205].

Most alternative lead-free solders are tin-based¹. Popular alloys are Sn-Cu, Sn-Ag, and Sn-Zn [207], [208]. As a silver-free alternative to SAC, Sn-Cu has the disadvantage that it has a higher melting point. Sn-Zn has the disadvantage that it is susceptible to corrosion, but it has a lower melting point than SAC [209]. Thanks to this lower melting point, Sn-Zn alloys with additives have received more attention in research. For example, Sn-Zn-Bi shows good properties [210].

A benefit of HASL is that it is inexpensive. A limitation is that it is a nonplanar finish [203]. As such, it is mostly used in simpler applications.

Immersion silver is an alternate surface finish that may be used in more advanced applications. It is based on the following chemical reaction:



¹Tin also has a rather high social impact, mainly due to its production in Indonesia, Myanmar and Bolivia, which account for about one third of the global production. There are not many lead-free, tin-free, and silver-free solders. Indium-based solders may be considered, e.g., In-Bi [206].

The benefits are that it is a simple process and that it provides a planar surface finish. It is also compatible with lead-free soldering. The high conductivity of silver is useful for signal integrity in high-frequency applications [211]. A major limitation is that the surface tarnishes over time, resulting in a lower shelf life [203].

For more advanced applications or applications where reliability is important, gold plating is used as a surface finish. Two variants are electroless nickel immersion gold (ENIG) and electroless nickel electroless palladium immersion gold (ENEPIG). These surface finishes are more corrosion resistant [203]. Examples of applications where these surface finishes are used are applications in aerospace, medical devices, high-frequency electronics, etc. However, ENIG and ENEPIG are significantly more expensive due to the price of the materials and the complexity of the process. As such, they are not a realistic alternative for the simpler applications where immersion silver might be used.

Organic Solderability Preservatives (OSPs) are another good alternative. They consist of a very thin organic coating which forms an organo-metallic compound with the copper surface [203]. Examples of OSPs are benzotriazoles ($C_6H_4N_3H$), imidazoles ($[(CH)_2NHCHN]$), and benzimidazoles ($C_6H_4(NH)CH$). Advantages are that they have a good solderability, they are low cost, and their fabrication is simple [212]. An additional advantage is that they are water-based and do not require mined ores. As such, they have a lower environmental and social impact. A major disadvantage of OSPs is their lower shelf life; however, there are recent advances in research towards a longer shelf life of two years, surpassing that of typical immersion silver [213]. As OSPs are not conductive, their application is limited to applications that do not require a conductive surface contacts [211].

6.3.2.2 Die-Wire bonding

In die-wire bonding, gold was originally used as a wire material. However, copper has replaced gold where possible, as it has a lower cost. As copper wire has a high hardness and low reliability, it does not perform well in high-end applications. Silver is being researched as a new material for bonding wire to replace gold in these applications, but it still presents many problems. Many materials are being researched to dope silver, in order to mitigate these problems. For example, adding palladium and gold may reduce electromigration, and cerium and lanthanum may increase the corrosion resistance [214].

As silver is being researched as an alternative to gold for applications where copper is not sufficiently reliable, copper is not considered to be an alternative to silver in this application. The main alternative is to continue using gold for wire bonding, which is not favoured by industry due to gold's high price.

6.3.2.3 Inner Electrode in Ceramic Capacitors

Multilayer ceramic capacitors (MLCC) consist of a stack of up to more than 1000 ceramic (dielectric) layers, alternated by inner electrode layers. This configuration makes it possible to reach very high capacitive values at low dimensions, enabling downsizing [27]. A schematic diagram of MLCCs is shown in Figure 6.5. The internal electrodes may be base metal electrodes (BMEs), based on nickel, or precious metal electrodes (PMEs), based on silver-palladium alloys. In PME, the terminal electrode consists of the farthest inner electrode, a barrier layer of nickel to prevent silver from dissolving into the solder, and, finally, a layer of tin or solder [215]. In an analysis of the main composition of metals in a PME MLCC, it has been shown that they typically contain 5 wt.% of silver [216].

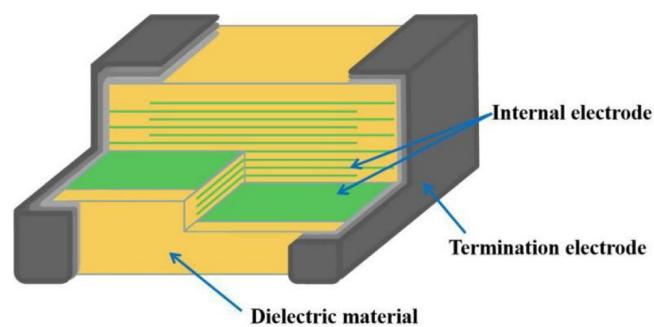


Figure 6.5: Schematic diagram of MLCC. Taken from [216]

Due to the high price of PMEs, there has been a move from PMEs to BMEs. PME-based MLCCs provide a higher reliability due to the TCE compatibility with the glass dielectric; however, BME-based MLCCs are less expensive, and there have been great improvements in terms of reliability and performance. As such, they are widely used in commercial applications. PMEs are mostly used in applications where there might be high thermal stresses and reliability is important. It is believed that BME will evolve to be the dominant technology, also for applications that need high-reliability capacitors. For most applications, these already present a good alternative to the silver-containing PMEs [217].

6.3.2.4 Electrically Conductive Adhesives

Electrically conductive adhesives (ECAs) are used in flip chip applications and as die attach adhesives. They consist of a non-conductive polymer matrix and conductive fillers. There are four types of filler materials: metal fillers, carbon fillers, ceramic fillers, and metal-coated fillers. For metal fillers, the most widely used materials are silver, gold, nickel, and copper. A disadvantage is the risk of electromigration [218].

Silver possesses the highest electrical conductivity of all metals [219]. As such, it is a widely used filler material for ECAs. Additionally, silver may be added in many forms: flakes, particles, wires, nanorods, etc. Other metal

fillers are nickel, gold, and copper. While gold has many advantages, such as its good resistance to corrosion and oxidation, its main disadvantage is that it is expensive. Nickel has good resistance to oxidation as well and is less expensive, but has a high resistivity, which is a major disadvantage for ECA applications. Finally, copper may be an alternative filler: it has high conductivity, it is not expensive, and it has good electromigration characteristics. However, it is prone to oxidation. Recent advances show that surface treatments of copper, e.g., a silver coating, may mitigate this issue [218].

It is clear from [218, Table 2] that the only alternatives to silver-based ECAs with similar electrical resistivity/conductivity are graphene, silver-coated nano graphite, and silver-coated copper (flakes). Graphene might be a valuable alternative to silver-based ECAs. However, bulk-scale graphene production is limited due to the high cost [220].

Chapter 7

Social Impact VS Environmental Impact

There is more to sustainability than social impact: environmental impact and economic feasibility also play a role. In the previous chapter, economic considerations were discussed when comparing different alternatives. In this chapter, the environmental impact of different materials will be studied and compared to the social impact. To do so, the following paper is used: "Selecting alternative metals for advanced interconnects" [7].

This paper compares alternative materials for advanced on-chip interconnects based on their technical properties and their environmental impact. While it does not consider the full scope of materials discussed in this work, this paper is selected as an example because of its thorough analysis, both technically and environmentally.

Currently, copper is mostly used to form interconnects. As outlined in subsubsection 6.2.2.3, the need for diffusion barriers is an obstacle in the downscaling of these interconnects. Additionally, the resistivity of copper increases at reduced dimensions and the metalization process has many challenges to overcome, including mechanical instability when downsizing. To mitigate these challenges, the ideal alternative metal does not require barrier and liner layers and exhibits a lower sensitivity of the resistivity to nanoscale dimensions [7].

First, promising alternatives were selected from elemental, binary, and ternary metals based on an analysis of: (1) the sensitivity of resistivity to nanoscale dimensions, (2) reliability, and (3) integration and process considerations. For selected alternative materials, the environmental impact is analysed through different sustainability aspects (SAs) [7].

Based on criteria (1) and (2), the following materials were selected: Cu, W, Mo, Ru, Ir, Rh, NiAl, CuAl_x, Al₃Sc, PtCoO₂ (delafossite), and Cr₂AlC (MAX). Of these, Cu, Al, Ni, Ru, Co, Mo, Ir, and Rh were selected for further sustainability analyses. As W and Pt were not included in the sustainability analysis of [7], but were included

in the sustainability analysis in [221], their performances will be added in this work, in order to provide a more complete overview.

The following SAs are considered in the analysis: supply risk (SA1), criticality and conflict (SA2), metal circularity within IC manufacturing (SA3), climate change impact (SA4), water scarcity (WS, SA5), impact on natural resources (SA6), and human health impact (SA7). SA1 is evaluated using the Herfindal-Hirschman Index to assess market concentration, SA2 is evaluated using the EU and US CRM lists and the EU conflict mineral list, SA3 is evaluated using the site material circularity index, SA4 is evaluated through global warming potential (GWP), SA5 is evaluated using the EF3.1 methodology for upstream water use, SA6 is evaluated using abiotic resource depletion potential (ADP), and SA7 is evaluated using EF 3.1 methodologies for human toxicity cancer and non-cancer, and particulate matter [7][221].

SA1 and SA2 are considered to refer more to economic sustainability, and in a smaller extent to social impact through conflict. SA3 is not reported in the original paper. As such, SA1, SA2, and SA3 are not reported in this work. In the original paper, SA7 is considered to be a social factor. However, it covers a part of social impact that has not been covered in this work, and the human health impact is closely related to environmental factors. As such, it is included in this chapter.

The environmental indicators per SA are shown in Table 7.1. The colouring is taken from [221] and corresponds to the following: **blue** indicates that the value lies in the lowest quartile of all materials, **yellow** indicates that the value lies in the second quartile of all materials, **orange** that the value lies in the third quartile of all materials, and **pink** that the value lies in the highest quartile of all materials. **Grey** indicates that no data were available for the indicator. The original paper [7] combines the first and the second quartiles in one colour. The division into quartiles is done manually, based on the information available in [221]. For W and Pt, [221] provides values relative to those of copper. The values reported in Table 7.1 are absolute values calculated based on the information in [221].

The social impact categories for this selection of material are shown in Table 7.2 and Table 7.3.

Material	SA4: GWP (kg CO ₂ /cm ³)	SA5: WS (m ³ /cm ³)	SA6: ADP (kg Sb Eq / cm ³)	SA7: Human Tox- icity (CTUh/cm ³)	SA7: particulates (dis- ease incidences / cm ³)
Copper (Cu)	0.0251	0.02	2.42×10^{-4}	2.42×10^{-6}	5.11×10^{-9}
Nickel (Ni)	0.0579	0.03	1.07×10^{-4}	2.05×10^{-7}	8.27×10^{-8}
Molybdenum (Mo)	0.0583	0.02	2.25×10^{-3}	9.20×10^{-6}	2.00×10^{-9}
Aluminium (Al)	0.0222	0.01	1.13×10^{-10}	1.46×10^{-8}	6.84×10^{-9}
Cobalt (Co)	0.0739	0.34	4.18×10^{-6}	3.38×10^{-8}	3.12×10^{-8}
Ruthenium (Ru)	26	164	3.34	1.98×10^4	...

Material	SA4: GWP (kg CO ₂ /cm ³)	SA5: water scarcity (m ³ /cm ³)	SA6: ADP (kg Sb Eq / cm ³)	SA7: Human Tox- icity (CTUh/cm ³)	SA7: particulates (dis- ease incidences / cm ³)
Rhodium (Rh)	436	152	2.61×10^{-5}	3.35×10^{-3}	4.75×10^{-5}
Iridium (Ir)	198	200	3.14	1.12×10^{-3}	...
Tungsten (W)	0.244	0.284	5.4×10^{-4}	6.53×10^{-7}	1.57×10^{-7}
Platinum (Pt)	268	231	21.5	1.97×10^{-3}	1.41×10^{-4}

Table 7.1: SA for current and alternative interconnect metals. Taken from [7] (Cu, Ni, Mo, Al, Co, Ru, Rh, and Ir) and calculated from [221] (W and Pt). Shading adapted from [221].

Material	Child Labour	ASM	HCB	Rule of Law	Corruption	HDI
Copper (Cu)	1.55 (61%)	2.15 (61%)	1.30 (61%)	1.62 (61%)	0.95 (61%)	0.77 (61%)
Nickel (Ni)	0 (66%)	2.43 (80%)	1.11 (73%)	1.95 (73%)	1.85 (73%)	0.83 (73%)
Molybdenum (Mo)	1.53 (91%)	1.93 (91%)	1.07 (91%)	1.69 (91%)	0.84 (91%)	0.63 (91%)
Aluminium (Al)	1.24 (84%)	2.35 (84%)	0.68 (84%)	1.63 (84%)	1.42 (84%)	1.22 (84%)
Cobalt (Co)	1.82 (76%)	2.71 (85%)	2.66 (85%)	2.73 (85%)	2.66 (85%)	2.48 (85%)
Ruthenium (Ru)	0.12 (97%)	1.11 (100%)	1.06 (100%)	1.14 (100%)	2.04 (100%)	1.01 (100%)
Rhodium (Rh)	0.17 (93%)	1.16 (100%)	1.11 (100%)	1.22 (100%)	2.00 (100%)	0.96 (100%)
Tungsten (W)	1.82 (94%)	1.85 (97%)	0.89 (97%)	2.03 (97%)	1.22 (97%)	0.99 (97%)
Platinum (Pt)	0.26 (87%)	1.25 (98%)	1.18 (98%)	1.34 (98%)	1.95 (98%)	0.90 (98%)

Table 7.2: Materials and their performance on indicators

As Iridium was not considered in the final selection in chapter 2, a separate analysis is made, following the steps outlined in chapter 4. The three producers are: South Africa (88.9%), Zimbabwe (8.1%), and Russia (2.9%). The final performance is given in Table 7.3

Material	Child Labour	ASM	HCB	Rule of Law	Corruption	HDI
Iridium (Ir)	1.17 (97%)	1.19 (100%)	1.06 (100%)	1.22 (100%)	2.08 (100%)	1.05 (100%)

Table 7.3: Performance social impact categories Iridium

From the data in Table 7.1, it is clear that copper, nickel, aluminium, and cobalt have a low environmental impact, while ruthenium, rhodium, platinum and iridium have a high environmental impact. However, when considering the data in Table 7.2 and Table 7.3, it becomes clear that cobalt, aluminium, tungsten and nickel have a higher

social impact than ruthenium, rhodium, platinum, and iridium. This proves that it is not straightforward to pick an 'ideal' material; nor in terms of technological advantages and disadvantages, nor in terms of sustainability.

Chapter 8

Conclusion

This work aims to provide an assessment of the social impact of electronics fabrication by assessing the social impact of the mining of materials essential to the fabrication of PCBAs. First, an overview of the materials used within the fabrication process of PCBAs was made. Then, a framework was proposed to assess social impact. This framework was applied to the selection of materials to assess the social impact per material. For each of the materials, the consumption by the electronics industry was also assessed. By combining social impact and industry consumption, three materials were selected for an analysis of their alternatives in their main applications. Finally, a comparison between social impact and environmental impact was made.

The overview of the materials used within the fabrication process of PCBAs is given in Table 2.1. The social impact of these materials is assessed through the following social impact categories: child labour, violent conflict, artisanal and small-scale mining, rule of law, control of corruption, and human development. The assessment happens on a country-by-country basis, which has the advantage that it allows for an analysis at a global level, and allows to efficiently assess all materials. Additionally, by working on a country-by-country basis, the indicators are available in a consistent way across the countries, from transparent and trustworthy sources. In future works, the assessment could be expanded by including data per region or even per mine. The analysis could also be expanded to other production steps, beyond mining, in order to provide a more complete assessment.

Cobalt and tantalum are the two materials with the highest social impact. Other materials with a high social impact are tin, antimony, and barium. Zirconium, hafnium, lithium, lead, and platinum are the materials with the lowest social impact.

The share of the global production consumed by the electronics industry is assessed in order to gauge the im-

part of possible changes within the electronics fabrication process. Materials with a high consumption by the electronics industry are beryllium, copper, gallium, ruthenium, silver, and tantalum. Materials with a low consumption by the electronics industry are barium, boron, chromium, iron, lanthanum, lead, lithium, manganese, molybdenum, phosphorus, titanium, tungsten, and vanadium.

Due to their high social impact, cobalt and tantalum were selected for a more detailed analysis. Due to its high consumption by the electronics industry and its relatively high social impact, silver was added to the selection. For each of these materials, alternatives for popular applications were discussed in terms of technological properties and cost. While for some applications alternatives exist, they mostly result in a trade-off between technological properties and cost.

By comparing the social impact and the environmental impact of a selection of materials, it becomes clear that an 'ideal' material does not exist. For example, cobalt has a low environmental impact, but a high social impact, while platinum has a high environmental impact, but a low social impact.

In conclusion, this work proposes a framework for assessing the social impact of electronics fabrication. The proposed framework provides an efficient and reliable method to assess social impact, and as a result, provides an assessment at the global level of the electronics industry as a whole. The assessed social impact may be used to support making design choices: a trade-off between technological properties, cost, environmental impact, and social impact.

Chapter 9

Societal reflection

9.1 The position of this work

The making of this work demands, to an extent, an expression of morality: social impact categories are scored, and countries are ranked based on what is regarded as high or low social impact. I.e., a low child labour rate is considered to be 'good' and to have a low social impact.

The selection of these social impact categories and corresponding indicators is coloured by my personal frame of reference. My frame of reference was formed by my environment. Many of these values could be considered to be collective: being against child labour or believing corruption is problematic. However, the extent of this 'collectivity' might be limited to those who live in a similar society or have a similar background. While the selection of criteria was based on available literature and frameworks, it must be noted that these are mostly published and developed by other highly educated Western people. As such, the reference frames of the authors consulted in this work are not as diverse.

Some of the used indicators, i.e., HDI and WGI, were criticized for this very reason. While aware of these criticisms, I still decided to use the sources as they provided a comprehensive and consistent overview of all countries of interest. Within the top-down approach I used, it is essential to use such sources. Which begs the question: was a top-down approach the right approach?

While a top-down approach allows for analysing many countries and materials comparably, it overlooks maybe the most important part of social impact: the experiences of the people who have to endure the impact. As many of the major primary producing countries are in the Global South, this effect increases by using indicators defined by a 'western' point of view. A bottom-up approach with qualitative input from the local population

would allow for a more complete analysis, less bound to my own frame of reference. However, within the scope of an engineering thesis, this approach was not an option. Additionally, beyond the scope of this thesis, such an approach would take a massive of time and resources before an analysis at the same global level could be made.

A missing part in this work is the fact that the absence of mining may also have a negative impact. Unlike environmental impact, social impact does not necessarily start from a 'neutral' state. The presence of mining might have many advantages, e.g., it might provide economic livelihood in a region that was previously riddled with poverty. While these considerations were explored in the section on artisanal and small-scale mining, it leaves me with the question: who am I to regard a mining operation as detrimental because it involves child labour by 16-year-olds, while I have always grown up in a safe house, where food, clothes and warmth were never a concern? Would it be better to not have the mining operations, but leave a child hungry? This question is only further complicated when one tries to take into account colonial history, imperialism and neocolonialist exploitations.

Keeping these considerations in mind, I have tried to provide a tool that is clearly substantiated and supported by objective (not neutral) sources. I leave it to the user to make a personal trade-off between the different social impact categories.

9.2 The role of engineers

'The user', in this case, is, hopefully, engineers. Which brings me to another aspect of morality. While the existence of this work implies that I believe that social impact *should* be taken into account, it is not my goal to declare that there is a right way to do so. As stated earlier, I believe each engineer should make a calculated trade-off based on different aspects, instead of solely efficiency. Not only between social impact aspects, but also between social impact, environmental impact, cost, and technological properties. In what follows, I will discuss my own idea of this trade-off.

The consideration of this trade-off starts with: Who do we serve? Society? Our neighbours? Our planet? Our world? Our company? Our country? Ourselves? Depending on the answer, the trade-off between social impact, environmental impact, cost, and technological properties will be very different. Even then, the trade-off will heavily depend on the application: for medical applications, the weight will be more on the impact on the user and technological properties than on the environmental impact. The question is, however, whether this same weight should be given to new phones with ever better cameras. I don't believe so, and I believe that making

this trade-off should be a deliberate decision in every design process.

Within my formation, I have often felt like we learned how to design systems that fulfilled certain specifications, without stopping and asking ourselves *who* made these specifications. And *why*. And who was *missing* in that conversation. I hope that this work provides a voice to those often missing in the conversation.

9.3 The role of technology

The discussion of the role of engineers cannot be held without talking about the role of technology in our society. I would like to refer to Kranzberg's first law of technology: "Technology is neither good nor bad; nor is it neutral". I am charmed by this outlook, as it implies the need to reflect on technology. People may be quick to state that technology is inherently good or bad; by making it clear that it is neither, one is forced to reflect on the context of its development and applications.

As I was finalising this work, Pope Leo XIV published an Encyclical Letter on AI and technology. I found the following passage striking, as it resembles what Kranzberg posed four decades ago: "Technology has the power to heal, connect, educate and protect our common home; but it can also divide, exclude and generate new forms of injustice. In the abstract, technology in and of itself is not a solution to humanity's problems, just as it is not inherently evil. In practice, however, technology is never neutral, because it takes on the characteristics of those who devise, finance, regulate and use it." He argues that the primary choice is not a 'yes' or 'no' to technology, but rather to what end we use technology: to unite or to divide. I would like to finish this work by pleading that we, as engineers, and as a society, strive for the former. And that in doing so, we do not lose sight of the 'invisible' (social) impact of our technological advances.

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Appendices

Appendix A: Popularisende samenvatting (NL)

Van tandenborstels over wasmachines tot auto's: alles lijkt de afgelopen jaren wel 'slim' te zijn geworden. Om dit mogelijk te maken, zit in elk van die apparaten minstens één elektronische chip. In een moderne auto kunnen zelfs duizenden elektronische chips zitten. De elektronica-sector is in de afgelopen decennia dus sterk gegroeid. Deze ontwikkeling brengt veel gevolgen met zich mee. Niet enkel voor het leven van de mens, dat in de afgelopen decennia toch sterk veranderde, met alle gevolgen vandien, maar ook voor de planeet.

De groeiende vraag naar elektronische chips gaat gepaard met een groeiend verbruik van grondstoffen. Daarnaast wil men steeds snellere en kleinere chips ontwikkelen om nieuwe toepassingen mogelijk te maken. Dit is enkel mogelijk met steeds specifiekere grondstoffen. Toch gebeurt er vrij weinig onderzoek naar hoe duurzaam de elektronica-sector is.

Waar er wel (beperkt) onderzoek bestaat naar de impact van de elektronica-sector op de planeet, blijft de menselijke impact onderbelicht. Toch is dit een belangrijk aspect: verschillende van de materialen die essentieel zijn voor de ontwikkeling van nieuwe, snelle elektronische chips, worden in slechte menselijke omstandigheden gedolven. Denk bijvoorbeeld aan tantalum: dit materiaal is belangrijk om kleine condensatoren te produceren, maar wordt ook gelinkt aan de oorlog die momenteel woedt in Oost-Congo.

Dit werk probeert een antwoord te formuleren op de volgende vraag: "wat is de menselijke impact van de elektronica-industrie?". Om deze vraag te beantwoorden, werden er enkele zaken afgelijnd. Om een inschatting te kunnen maken van de volledige industrie, en bijvoorbeeld niet enkel van de smartphone-industrie, wordt gekeken naar de productie van *Printed Circuit Board Assemblies* (PCBAs). Dit zijn de elektronische componenten die eigenlijk in elke elektronische toepassing wel voorkomen. Hierdoor kan ook de kost van, bijvoorbeeld, elektronica in auto's en huishoudapparaten meegenomen worden.

PCBAs bestaan uit drie grote onderdelen: PCBs, chips, en passieve componenten. De materialen die van pas

komen in de productie van deze componenten werden opgelijst. Voor deze materialen werd de sociale impact geanalyseerd. Dat gebeurde door te focussen op de menselijke impact tijdens het ontginnen van deze materialen. Er werd gekozen om op deze productiestap te focussen, omdat er aangetoond is dat de grootste risico's voor de mens plaatsvinden tijdens de ontginningsfase.

De sociale impact tijdens de ontginningsfase werd op het niveau van de producerende landen bepaald. Dit gebeurde aan de hand van de volgende parameters: kinderarbeid, artisanale en kleinschalige mijnbouw, de aanwezigheid van gewapend conflict, de sterkte van de rechtsstaat, de controle van corruptie en de *Human Development Index* (HDI). Elk van de producerende landen kreeg per parameter een score toegekend. Per parameter werd dan een eindscore berekend door een gewogen gemiddelde te berekenen. Dit gemiddelde werd gewogen met het aandeel in de wereldproductie van elk producerend land.

Het resultaat van deze bewerkingen is een oplijsting van de gewogen gemiddelde score per parameter voor elk materiaal. Op deze manier kan de lezer een idee krijgen van de menselijke impact van elk materiaal. De materialen met de grootste negatieve impact waren kobalt en tantaal.

Na het berekenen van een score per parameter voor elk materiaal, werd ook nagegaan voor welke materialen de elektronica-sector een belangrijke gebruiker is. Dit laat toe om in te schatten of veranderingen binnen de sector een grote impact kunnen hebben. Daaruit bleek dat van beryllium, koper, gallium, ruthenium, zilver en tantalum de grootste aandelen worden gebruikt door de elektronica-industrie.

Voor kobalt, tantaal en zilver werd nagegaan of er alternatieve materialen bestaan om te gebruiken in het productieproces van PCBAs. Die bestaan, maar brengen steeds een nadeel met zich mee: kostprijs, chemische of fysische eigenschappen...

Ten slotte wordt de sociale impact van bepaalde materialen vergeleken met hun ecologische impact. Die vergelijking toont dat enkele materialen met een hoge sociale impact, bijvoorbeeld kobalt, een bijzonder lage ecologische impact hebben.

De afweging tussen de technologische vereisten, kostprijs, ecologische impact, en sociale impact, toont dat er geen ideaal materiaal bestaat. Elk materiaal heeft voor- en nadelen, en het is aan de ingenieur om een eigen afweging te maken.

Appendix B: Use of Generative AI

Grammarly

Grammarly was constantly used as an add-on while writing this thesis. I used the free version, so the tool functioned as an additional spelling and grammar check. I rarely used the suggestions for more clarity, as they are not included in the free version.

Example of such a correction are: "All together" → "Altogether" and "In an ion implantation machine the ions are extracted from the source, e.g. AsH_3 , PH_3 , SbF_3 or BF_3 " → "In an ion implantation machine, the ions are extracted from the source, e.g., AsH_3 , PH_3 , SbF_3 or BF_3

Claude and ChatGPT

I used these two genAI tools for various purposes. Below, an overview is given, as well as some example prompts. Altogether, I started 6 chats (thematic cluster of prompts) in Claude and 12 in ChatGPT.

- Tips for visualization in Excel, example prompt:
'have excel with percentage bar, but color based on value of left cell'
- Tips for visualization in LaTeX, example prompt:
'multiple lines in longtable latex. How to change distance between two lines to 1 instead of 1.5'
- Generation of visualization in LaTeX from Excel table, example prompts:

Make table of following data for latex:

I want heading to be bold

I want the cell of the second column to be of background: green if < 5, yellow if 5-10, orange if 10-15, red if >= 15

I want the cell of the third column to be of background: green if <0.01, yellow if 0.01-0.5, orange if 0.5-1, red if >=1

I want the cell of the fourth column to be of background: green if <3, yellow if 3, orange if 4, red if 5

I want the cell of the fifth column to be of background: green if >= 1, yellow if 0-1, orange if -1 to 0, red if <= -1

I want the cell of the sixth column to be of background: green if >= 1, yellow if 0-1, orange if -1 to 0, red if <= -1

I want the cell of the seventh column to be of background: green if ≥ 0.8 , yellow if 0.7-0.8, orange if 0.55-0.7, red if ≤ 0.55

If cell contains ND: gray background

Country	Child labour % in economic activity	Percentage of ASM miners	Heidelberg conflict barometer	WGI Rule of Law	WGI Control of Corruption	HDI
Argentina	2,0	0,01	1	-0,25	-0,33	0,865
Australia	0,0	ND	0	1,47	1,85	0,958
[...]						

and

Report this table in the following format: first column (chemical symbol) & second column (third column), fourth column (fifth column), sixth column (seventh column), eighth column (ninth column), tenth column (eleventh column)

Place a % before every %

End every line with `\hline`

Barium	India	29,9%	China	26,3%	Kazakhstan	12,1%	Morocco	10,0%	Mexico	3,8%
[...]										

I was worried about values being changed in the output, so I made sure to double-check every value with the original input.

- Help with errors in LaTeX and Python, example prompts:

```
File "c:\Users\celle\Downloads\Cuba MICS6 Datasets\test.py",
line 2 test = pandas.read_spss("C:\Users\celle\Downloads\Cuba MICS6 Datasets\Cuba MICS6
SPSS Datasets\fs.sav")
^SyntaxError: (unicode error) 'unicodeescape' codec can't decode bytes in position 2-3:
truncated \UXXXXXXXX escape PS C:\Users\celle\Downloads\Cuba MICS6 Datasets>
```

and

```
INFO - This is Biber 2.18 INFO
- Logfile is 'main.blg' ERROR
- Cannot find 'main.bcf'! INFO
```

- ERRORS: 1

latex via vscode

Deepl Write

The Deepl Write Academic Paraphraser Tool was used to reformulate some of the paragraphs where I was not too sure about clarity and structure. The tool can be accessed through: <https://www.deepl.com/en/write/academic-paraphraser>. An example of input, output, and final product is given below.

Input

As IC technology is based on semiconductors, doping is an important fabrication step: it creates the n-doped and p-doped regions, which lie at the base of electronic functioning. To end up with functional electronic units, the different regions must be patterned correctly and then interconnected through a specific stack of patterned conducting and insulating layers. This fabrication process is mostly photolithography-based: the different layers are patterned using photolithography. The most common fabrication steps used between the photolithography steps are etching, oxidation, deposition, implantation, and planarization [25, Chapter 4].

Fabrication is split into two phases: front-end of line (FEOL) and back-end of line (BEOL). During FEOL, the different components are patterned in the silicon. During BEOL, the different components are connected through interconnections and wiring. Both FEOL and BEOL use similar production steps, but on different materials.

Output

As IC technology is predicated on semiconductors, doping constitutes a pivotal fabrication step. This process engenders the n-doped and p-doped regions, which form the foundation of electronic functioning. In order to achieve functional electronic units, it is essential that the different regions are patterned correctly and then interconnected through a specific stack of patterned conducting and insulating layers. The fabrication process is predominantly photolithography-based, whereby the various layers are patterned using photolithography. The most common fabrication steps utilised between the photolithography steps are etching, oxidation, deposition, implantation, and planarization [25, Chapter 4].

The fabrication process is divided into two distinct phases: front-end of line (FEOL) and back-end of line (BEOL). During the Front-End Of Line (FEOL) process, the various components are patterned in the silicon. In the course of the BEOL process, the various components are interconnected and wired. It is evident that the FEOL and BEOL manufacturing processes utilise comparable production steps; however, these steps are executed on disparate materials.

Final text

As IC technology is based on semiconductors, doping is an important fabrication step. This process creates the n-doped and p-doped regions, which lie fundamental to electronic functioning. In order to produce functional electronic units, the different regions must be patterned correctly and then interconnected through a specific stack of patterned conducting and insulating layers. The fabrication process is mostly photolithography-based as the different layers are patterned using photolithography. The most common fabrication steps used between the photolithography steps are etching, oxidation, deposition, implantation, and planarization [25, Chapter 4].

The fabrication process is divided into two phases: front-end of line (FEOL) and back-end of line (BEOL). During the FEOL process, the different components are patterned in the silicon. During the BEOL process, the components are connected through interconnections and wiring. Both FEOL and BEOL processes use similar production steps, but on different materials.

