Facilitating Sustainable Material Decisions: A Case Study of 3D Printing Materials

by

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Professor David Dornfeld, Co-Chair (Posthumous Recognition)
Professor Tarek Zohdi
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Abstract

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The rapid increase in material use and goods produced in the global market is leading to harmful consequences for the environment and for human health. As consumption continues to increase, it is crucial to address the impacts associated with decisions about choices of materials used. Integrating safer material decisions during the product design and development process will lead to less harmful environmental and human health effects. Moreover, the sustainable performance of products depends on the choices of materials that go into those products.

This research seeks ways in which sustainable performance might become a more integral part of the materials choice process and aims to facilitate sustainable material choices during the product development process. Initially, the goal of the research was to create a tool that maps the trade-offs between material costs, performance and environmental impact, using 3D printing materials as a case study. Thirty-six 3D printing material filaments were examined for this research. For each filament, it's description, base composition, mechanical properties, printing guidelines and hazards were collected. As empirical research progressed, however, it became clear that there are significant barriers to integrating sustainable material choices into the product development process that must be overcome in order to do so. This dissertation aims to clearly identify those barriers, including the significant complexity associated with gathering accurate data to feed a tool.

The tool created here is presented as a set of specifications for how a tool should work, with representations of outputs that have been tested with the potential audience for the tool. The dissertation thus addresses not only what a tool would have to do, but the changes needed in the system that surrounds such a tool to allow it to truly address material sustainability.

Dedicated to my parents.

Contents

List of Figures

List of Tables

Acknowledgments

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Chapter 1

Introduction

“In the past 50 years, humans have consumed more resources than in all previous history [1].” The world’s average material extraction per capita increased from 8.2 metric tons in 1980 to 11.8 metric tons in 2013 [2]. Moreover, in that 33 year period, the global material extraction rate increased by 132% from 36 billion metric tons to 85 billion metric tons per year [2]. In 2000, the United States alone consumed 57% more materials than in 1975 while the increase in global consumption was even higher [1].

The rapid increase in material use and goods produced in the global market is leading to harmful consequences for the environment and for human health. As consumption continues to increase, detrimental and irreversible effects to our ecosystem will spread, impacting future generations. It is crucial to address the impacts associated with decisions about choices of materials used and quantities consumed from a global level down to the product level. As industries and companies continue to use more materials to produce more products, integrating safer material decisions during the product design and development process will lead to less harmful environmental and human health effects.

During the mid-nineteenth and early twentieth century, chemists developed new approaches to chemistry that resulted in the creation of synthetic chemicals. As a consequence, the chemical industry revolutionized virtually all other industries such as agriculture, health care and pharmaceuticals, household products, transportation, construction and even warfare. The synthetic chemicals that were used to create everyday products were advertised as a means to providing a better life. Yet, little research was done to investigate the hazards associated with them and the effects they had on the workplace, environment and human health. Over the next few decades, the public started responding to increasing reports about the adverse effects that these synthetic chemicals were having.

Lead and arsenic were found in food, drugs and cosmetics, artificial sweaters contained carcinogenic dyes, and drinking water contained harmful levels of fluoride. By the 1970s, the Environmental Protection Agency (EPA) was created, along with the Clean Air Act and the Occupational Safety and Health Act, and the 1972 Clean Water Act to respond to and take action on multiple hazardous practices. Nonetheless, today in the US alone, there are over 70,000 chemicals used in industry in various materials and products [3] while the American Chemical Society state there are over 129 million unique substances registered worldwide. This makes it extremely difficult for any regulatory body to control every chemical in every product. Firms are still unknowingly using materials with adverse environmental and human health effects [4]. The approach with which products are designed and made needs to transform to include more assessment of the potential hazards of materials choices. As the research in this dissertation will show, approaches today rely primarily on using restricted substance lists authorized by government agencies, which is at best an incomplete view of a variety of other potential adverse effects of materials. The dissertation proposes a broader assessment of materials choices that allows for more complete evaluation.

This chapter briefly reviews the product development process in which materials choices are embedded, and then dives into materials selection approaches in more detail, providing the context for the processes on which the dissertation focuses. The chapter then addresses more deeply the efforts being made already to develop sustainable products, materials and chemicals, and what is missing from this work that this dissertation addresses. It closes with an outline of the rest of the dissertation.

1.1 Product Development Process

Formal descriptions of the product development process have only been around for 30-40 years. Early descriptions of design or product development processes focused on solving a problem [5]. Today much more detailed descriptions define the product development process as a sequence of steps and activities that an individual or enterprise follows in order to conceive, design and commercialize a new product [6].

At a high level, one of the earliest product design processes is the Waterfall Method by Royce [7]. Although it was written for software development, the process can be generally applied to other industries. It divides the development into a sequence of steps for analysis and coding, and involves feedback for each step throughout the process. Boehm [8] on the other hand created a spiral model for software development that more accurately represents the iterative nature of the process as it aims to mitigate risks in each round. Each cycle of the spiral identifies the objectives, alternatives and constraints, and uses prototypes, benchmarks or analysis to reduce risk and plan the next step. Others saw the design process as a general problem solving process that entailed analysis, synthesis and evaluation or decomposition of a problem to find the right components for each elemental part [5].

Many different representations of the design product development process exist. Yet, they all embody the same basic structure. As Sidky et al. [9] explains, the design process is fundamentally a problem analysis that is composed of problem identification and problem decomposition. As can be seen in Figure 1.1, problem identification is the process of understanding the customer's real problem, what the customer perceives, and what the customer desires. From this step, a problem statement is defined. Next, during the problem decomposition phase, the problem is divided into smaller elements to better understand the customer insights and translate them into customer needs. From this step, solutions are generated that address the customers' needs.

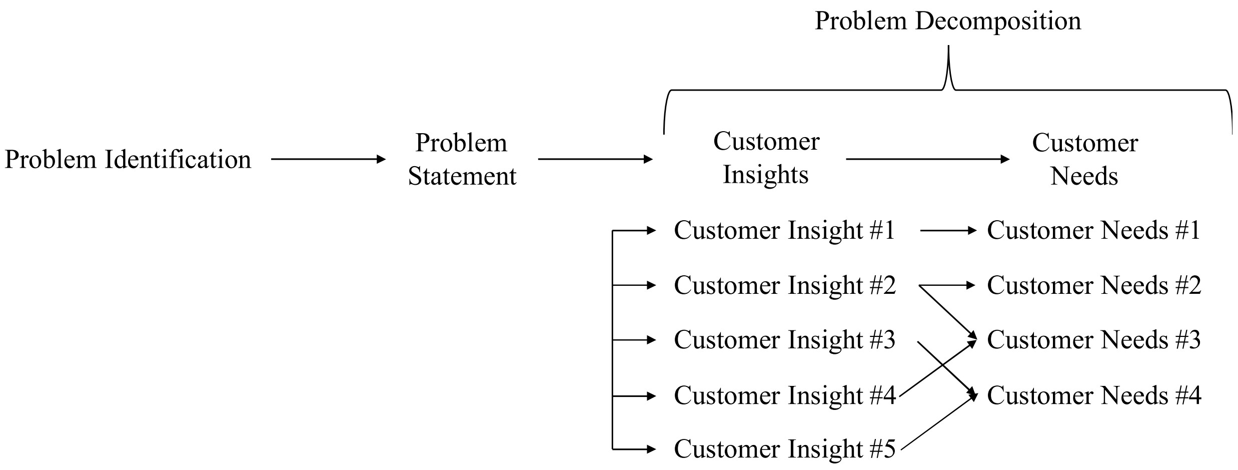


Figure 1. 1 Problem analysis: identification and decomposition, adapted from Skidy et al. [9]

Brown [10] describes a similar set of activities in a design thinking approach that involves three steps; inspiration, ideation, and implementation. These steps include defining the business problem and opportunity, observing how people think and what they want, brainstorming ideas that meet the customers' needs and then building and testing prototypes, until the idea is ready to execute. Beckman and Barry [11] articulate these steps as observation, insights, ideas, and solutions using a learning model of the design process. These descriptions allow for a more iterative view of the process that engages the customer throughout.

Ulrich and Eppinger's [6] product development process, highlighted in Figure 1.2, is another method that is widely used. It is broken into seven steps yet they are not absolutely sequential; rather each step is an iterative process and overlaps with other steps throughout the development process. It starts with identifying customer needs and establishing customer specifications. It then continues to concept generation, selection, and testing. Finally, the final product specifications are set and the downstream planning of, for example, the development schedule and resource requirements takes place. In addition, each step involves an economic analysis, benchmarking competitive products, and building and testing prototype models. Other similar product development processes have been described by Roozenburg and Eekles [12], Ullman [13], Pahl and Beitz [14], and Griffin [15].

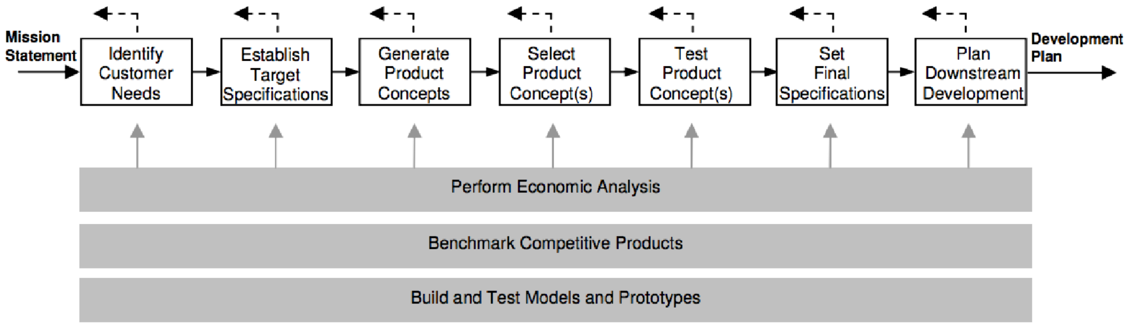


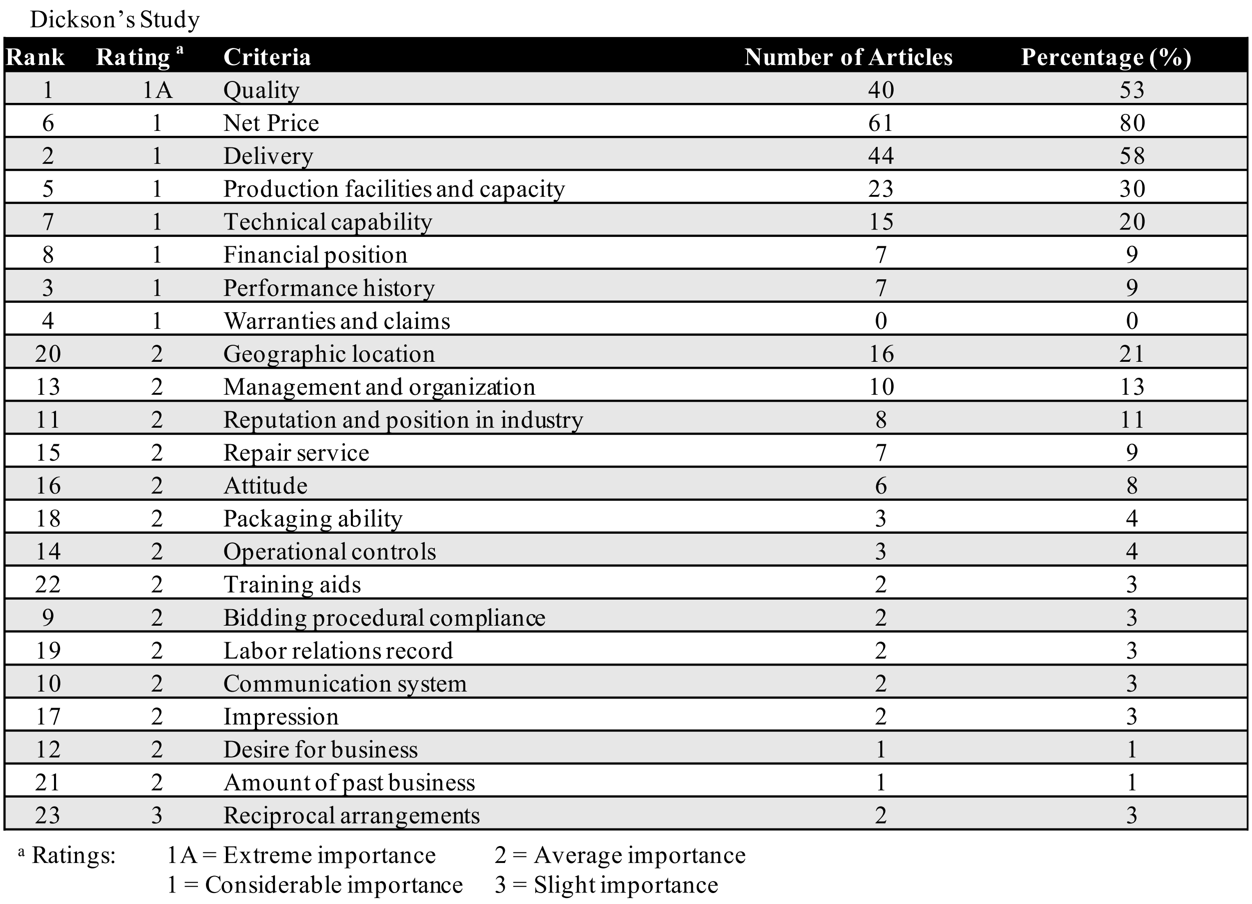
Figure 1. 2 Ulrich and Eppinger's product development process, adapted from Ulrich and Eppinger's [6]

In each step during the design process, multiple decisions need to be made and sometimes by multiple participants. Such decisions include identifying the most important customer needs to address, choosing the optimal product concept, and selecting the final specifications of the product such as its key components, tolerances and materials. Every decision is based on a set of criteria that need to be met that are unique to a given industry and even company. At a general level, those criteria generally involve the cost and time to design and develop the product, and measures of the product's performance for the customer (e.g., cost, quality, product performance). They sometimes include environmental and social impacts of the product as well. These general criteria are translated, as described in Figure 1.2, into the target specifications for a specific product development undertaking.

One of the most important decisions that is made in the product development process, generally during the generate and select product concepts stages shown in Figure 1.2, is materials choice. These choices affect the ability of the product to meet functionality, aesthetics, quality, safety and profitability goals. They also affect the ability to meet environmental and social performance goals when companies have them. We turn now to more closely examine materials selection processes.

1.2 Material Selection

Selecting materials during the product design process requires evaluating those materials against multiple criteria and ultimately making trade-offs. Several researchers have studied the criteria used by companies today. Xia et al. emphasize the importance of selecting the right material supplier to minimize cost, maximize quality, and maximize service performance [16]. Quality includes the need for high technical performance, low defects and high reliability materials and suppliers. Service includes on time delivery, short repair turnaround time, a long warranty period, and adequate supply capacity. Chatterjee et al. used the following criteria to rank and select materials: desired properties, operating environment, production process, costs, market value, availability of supplying sources, and product performance [17]. Weber took the analysis one step further and reviewed 74 articles on materials choice-making since 1996 and outlined 23 criteria used during the supplier selection process [18]. The 23 criteria can be seen in Figure 1.3 and are given a rating of importance where the most important criteria were quality, delivery, vendor performance history, warranties and claims, production facilities and capacity, net price, technical capability and financial position.



Dickson's Study

Rank	Rating [a]	Criteria	Number of Articles	Percentage (%)
1	1A	Quality	40	53
6	1	Net Price	61	80
2	1	Delivery	44	58
5	1	Production facilities and capacity	23	30
7	1	Technical capability	15	20
8	1	Financial position	7	9
3	1	Performance history	7	9
4	1	Warranties and claims	0	0
20	2	Geographic location	16	21
13	2	Management and organization	10	13
11	2	Reputation and position in industry	8	11
15	2	Repair service	7	9
16	2	Attitude	6	8
18	2	Packaging ability	3	4
14	2	Operational controls	3	4
22	2	Training aids	2	3
9	2	Bidding procedural compliance	2	3
19	2	Labor relations record	2	3
10	2	Communication system	2	3
17	2	Impression	2	3
12	2	Desire for business	1	1
21	2	Amount of past business	1	1
23	3	Reciprocal arrangements	2	3

[a] Ratings: 1A = Extreme importance 2 = Average importance
1 = Considerable importance 3 = Slight importance

Figure 1. 3 Vendor selection criteria and rating, adapted from Weber et al.[18]

Ashby defines material selection as a link between a material, the function it is required to perform, its desired shape and attributes, and the process required to make the shape [19]. Functional requirements are based on *metrics of performance* such as strength and density of the material [20]. Ashby emphasizes the need to first translate product design requirements into materials objectives and constraints in order to narrow materials choices and then rank the materials by their performance ability. Later, Ashby and Johnson also include the link between material and what they call context, the intention and mood it creates within the product, the personality given to the product by its aesthetics and associations, and finally its effect on product usability [21].

In addition to assessing materials for their contribution to product-based outcomes, designers many times must also consider the supply chain, whether lean, agile or hybrid, via which their materials will be produced and delivered. The Supply Chain Council constructed a framework to measure a company's performance, communicate supply chain issues and identify improvements [22]. The Standard Supply Chain process framework is divided into four categories; delivery reliability, flexibility and responsiveness; costs; and assets. These four categories are further divided into 12 metrics shown in Table 1.1 below [22].

Table 1. 1 The Standard Supply Chain framework categories and metrics, adapted from Wang et al.[22]

Categories	Metrics
Delivery Reliability	Delivery performance Fill rate Order fulfillment lead time Perfect order fulfillment
Flexibility and responsiveness	Supply chain response time Production flexibility
Cost	Total logistics management cost Value-added productivity Warranty cost or returns processing cost
Assets	Cash-to-cash cycle time Inventory days of supply Asset turns

After identifying important metrics to choose material suppliers and narrow material options, a number of methodologies might be used in order to choose the final material. The simplest option is to assign weights to the different selection criteria and create a hierarchy or ranking of the materials. Other options include mathematical modeling and optimization such as multidimensional optimization, analytic network processes, case-based reasoning, data envelopment analysis, fuzzy set theory, genetic algorithms and their hybrids. A review of these methodologies is given by Ho et al. [23]. Finally, digital software and online materials databases also help in making materials choices. A review of available databases is given by Ramalhete et al. [24].

As this section makes abundantly clear, materials selection is a complex process that can entail dozens of metrics among which a design engineer may have to make tradeoffs. Although there are many options for modeling this choice, and available online databases, the decision-making process remains a difficult one.

1.3 Importance of Integrating Sustainability

As more goods and services are produced to meet human needs, a deeper understanding of the interactions between society and nature must be taken into consideration. This concept has developed into what is now known as sustainable development. In 1987, the World Commission on Environment and Development (WCED) defined sustainable development as “development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs”. Over the years, the definition of sustainable development has evolved to incorporate three pillars of sustainability; social, economic, and environmental. Social sustainability refers to the social welfare and being of a country, community, family, organization or workers. It aims to end social injustice, diseases and poverty in order to provide people with food, education, and an equitable life [25]. Economic sustainability is the ability for a business to support itself and keep providing its goods and services [25]. Finally, environmental sustainability refers to maintaining environmental quality and natural resources, by using resources efficiently and decreasing pollution and other harmful effects on the environment [25]. By integrating these three pillars into everyday decisions, the WCED goal can be maintained. Figure 1.4 highlights the relationships among the three pillars of sustainability [26].

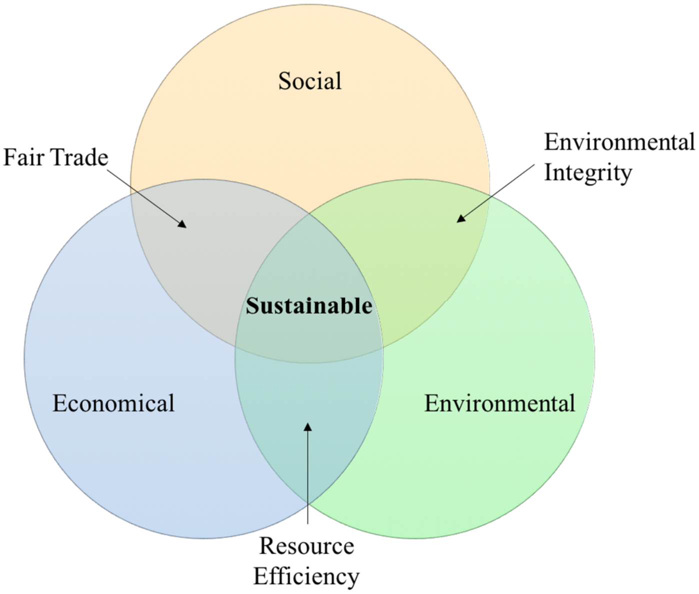


Figure 1. 4 Relationship between the three pillars of sustainability, adapted from Helu [26]

In order to achieve the three pillars of sustainability, individuals, companies and government organizations and have increasingly integrated sustainability assessments into their businesses.

A sustainability assessment is the practice of evaluating a current practice or activity in terms of sustainability. Pope et al. [27] evaluate three types of sustainability assessments; environmental impact assessment (EIA), strategic environmental assessment (SEA) and the triple bottom line (TBL). They examine the environmental, social and economic impacts of a proposal before and after it has been designed, as well as during design to see if it actually sustainable. Moldan et al. [28] review indicators and targets that have been developed in order to understand and measure environmental sustainability. Such indicators include deforestation, climate change, ozone layer protection, air pollution (such as SO_2, NOx, VOC), carbon dioxide emissions per capita, water resources used, terrestrial and marine areas protected, population with improved drinking water and sanitation as well as portion of urban population living in slums. Kates et al. [29] reviews 12 sustainable indicator initiatives, the number of indicators they have used, what it aims to sustain and develop as well as the time frame. They conclude that the range of indicators used is broad in order to account for varying stakeholders and the timeframe of “now” and “future” is ambiguous. Yet, the varying indicators and initiatives highlight that sustainable development is an evolving approach and is adaptable to fit any participant.

Thus, multiple metrics needed to evaluate the environmental impact of a materials choice have been defined.

1.4 Efforts Made to Develop Sustainable Products

As pressure increases on companies from new legislation and initiatives, as well as from growing consumer awareness and activism on the topics of sustainability, more sustainable approaches to design and manufacturing have been adopted in order to produce more sustainable products. Such approaches include conducting life cycle assessments and following design for the environment guidelines when developing products, using sustainable materials, and developing and using safer chemicals. Figure 1.5 highlights the relationships among chemicals, materials and products. Chemicals are used to create materials that then go into products, and are often used directly in making products as well. Improving the safety and sustainability of chemicals will thus lead to more sustainable materials and products.

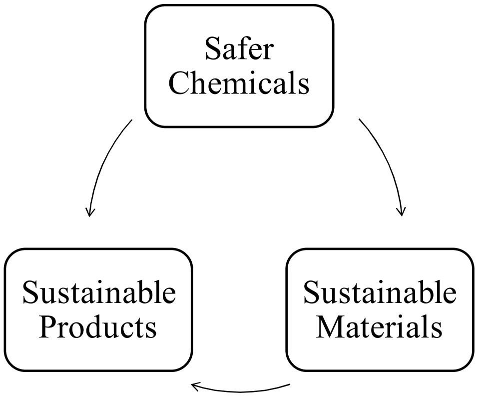


Figure 1. 5 Relationship between chemicals, materials and products

Sustainable Products

Life Cycle Assessments (LCA) and Design for Environment (DFE) are two approaches used by industry to assess and create more sustainable products. LCA is a standardized assessment framework used to analyze the environmental and social impacts of a product across all the stages of its life (Figure 1.6). The stages include raw material extraction, production, use, and end of life. A LCA starts with an inventory of inputs such as materials, energy, and water requirements to a system or product and of the output emissions that result from making the system or product, and evaluates the impacts of each input and output. Impact categories then translate into environmental themes such as climate change, ozone layer depletion, and acidification.

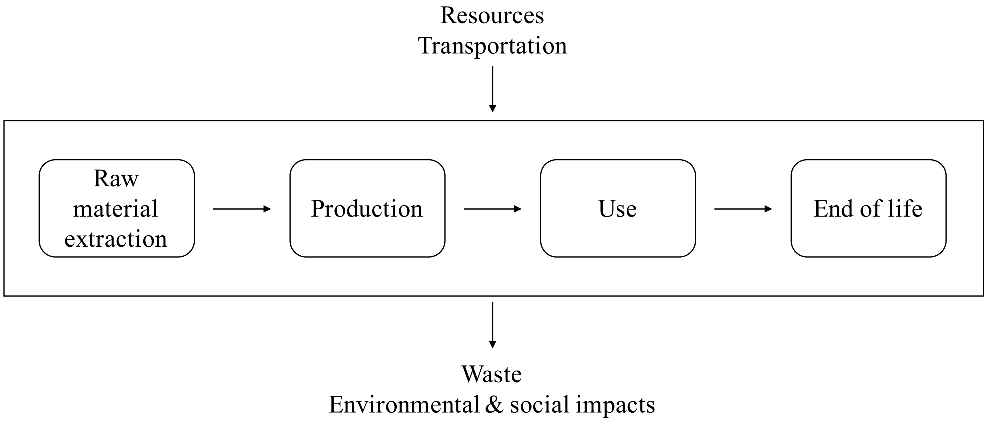


Figure 1. 6 Product life cycle stages and system, adapted from Helu [26]

Design for X is a systemic design process that is used when developing and producing a new product, that helps address a factor X. Many X factors exist, such as environment, manufacturing, and assembly. A list of DFX strategies can be found in Appendix A1. Design for the environment (DFE), also sometimes known as design for sustainability, provides a method to minimize environmental impacts of a product to create a more sustainable product and society.

Griffin et al. argue that design for the environment is an aspect of design for sustainability [15]. Design for sustainability aims to ensure goods and services at a competitive price that satisfy a need while reducing ecological impact and resource use throughout the life cycle. Design for the environment focuses on the performance of the design with respect to the environmental, health, safety and sustainability[1] objectives throughout the lifecycle. The DFE guidelines focus on the reduction of material, water and energy used to process the materials; reduction of toxic, hazardous or harmful characteristics in a product along with design for benign waste; recovering, recycling and reusing materials and energy to eliminate waste and reduce the consumption of virgin resources; and finally ensuring the safety of human, natural and economic resources. Figure 1.7 highlights where in the value chain these sustainability considerations, as well as social and economic considerations, are generally made. Note that materials choices may be involved at any of these stages in order to minimize resource use and cost and attain a more sustainable product.

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[1] The definition of sustainability encompasses environmental, societal, and economical considerations. For this thesis, sustainability and environmental performance will be used interchangeably.

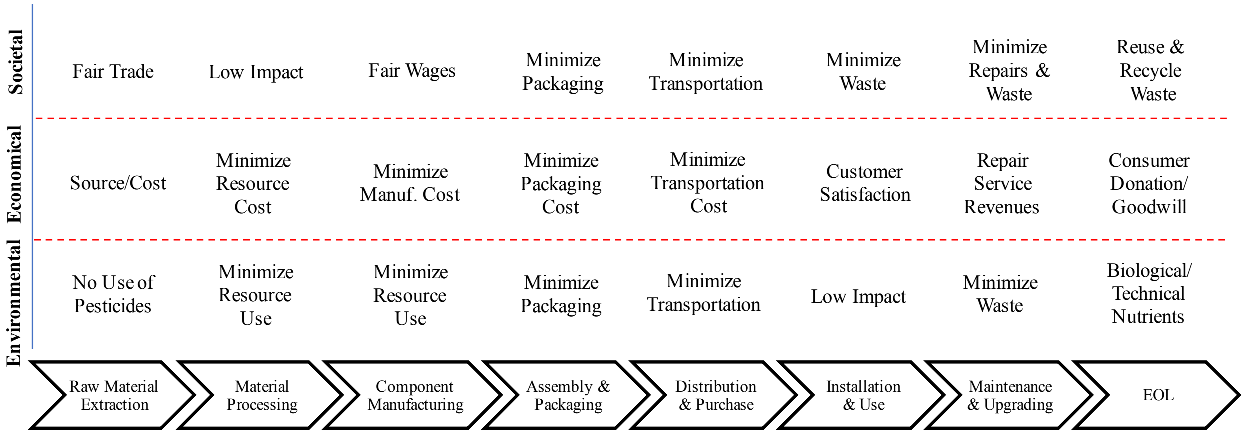

Figure 1. 7 Value chain of sustainable design thinking, adapted from Griffin et al. [14]

Ulrich and Eppinger [6] divide DFE impacts into two broad categories that must be taken into consideration during every stage of a product's life cycle; energy and materials. Energy refers to the use of less energy and the use of more renewable energy, while materials refers to the use of less materials and use of more recyclable materials. Ulrich and Eppinger categorize the environmental impacts that result from a product into global warming, resource depletion, solid waste, water pollution, air pollution, land degradation, biodiversity, and ozone depletion. Their DFE process consists of setting an agenda to identify internal and external drivers of DFE to highlight why the organization wants to address the environmental performance of its products and then set their DFE goals. Table 1.2 is an example Ulrich and Eppinger provide for DFE goals according to the product life cycle stages.

Table 1. 2 Example DFE goals according to the product life cycle stages, adapted from Ulrich and Eppinger [6] based off adapted work from Giudice et al. (2006)

Life Cycle Stage	Example Design for Environmental Goals
Materials	• Reduce the use of raw materials. • Choose plentiful, renewable raw materials. • Eliminate toxic materials. • Increase the energy efficiency of material extraction processes. • Reduce waste. • Increase the use of recovered and recycled materials.
Production	• Reduce the use of process materials. • Identify process materials that can be fully recovered and recycled. • Eliminate toxic process materials. • Select processes with high energy efficiency. • Reduce production scrap and waste.
Distribution	• Use the most energy-efficient shipping. • Reduce emissions from transport. • Eliminate toxic and dangerous packaging materials. • Eliminate or reuse packaging.
Use	• Extend useful life of the product. • Promote use of products under the intended conditions. • Enable clean and efficient servicing and operations. • Eliminate emissions and reduce energy consumption during use.
Recover	• Simplify product disassembly to separate materials. • Support the recovery and remanufacturing of components. • Facilitate material recycling. • Reduce waste volume for incineration and landfill deposit.

The next steps are to identify potential environmental impacts of the product during the concept development phase (Table 1.3) then select and apply DFE guidelines that help a team make early DFE decisions during their design process without conducting an environmental assessment. These guidelines are different than their goals and drivers, rather they provide instructions to reduce the environmental impacts of a product. Table 1.4 highlights some DFE guidelines arranged according to the product life cycle stages.

Table 1. 3 Questions for consideration of environmental impacts of a product according to the product life cycle stages, adapted from Ulrich and Eppinger based off work from Brezet and van Hemel (1997)

Life Cycle Stage	Questions
Materials	• How much, and what types of recyclable and non-recyclable materials will be used? • How much, and what types of additives will be used? • What is the environmental profile of the materials? • How much energy will be required to extract these materials • Which means of transport will be used to obtain them?
Production	• How many, and what types of production process will be used? • How much, and what types of auxiliary materials are needed? • What will be the energy consumption? • How much waste will be generated? • Can production waste be separated for recycling?
Distribution	• What kind of transport packaging, bulk packaging, and retail packaging will be used (volumes, weights, materials, reusability)? • Which means of transport will be used?
Use	• How much, and what type of energy will be required? • How much, and what kind of consumables will be needed? • How much maintenance and repairs will be needed? • What and how much auxiliary materials and energy will be required? • What will be the lifetime of the product?
Recover	• How can the product be reused? • Will the components or materials be reused? • Can the product be quickly disassembled using common tools? • What materials will be recyclable? • Will recyclable materials be identifiable? • How will the product be disposed?

Finally, the last stages involve assessing the environmental impacts of the product over its life cycle and comparing it to the DFE goals; refining the design to meet the goals; and reflecting on the process and results.

Table 1. 4 Design for environment guidelines according to the product life cycle stages, adapted from Ulrich and Eppinger [5] based off adapted work from Telenko et al. (2008)

Life Cycle Stage	**Design for Environment Guidelines**	
Materials	Sustainability of resources	• Specify renewable and abundant resources. • Specify recyclable and/or recycled material. • Specify renewable forms of energy.
	Healthy inputs and outputs	• Specify nonhazardous materials. • Install protection against release of pollutants and hazardous substances. • Include labels and instructions for safe handling of toxic materials.
Production	Minimal use of resources in production	• Employ as few manufacturing steps as possible. • Specify materials that do not require surface treatments or coatings. • Minimize the number of components. • Specify lightweight materials and components.
Distribution	Minimal use of resources in distribution	• Minimize packaging. • Use recyclable and/or reusable packaging materials. • Distribute products in a compact state. • Apply structural techniques and materials to minimize the total volume of material.
Use	Efficiency of resources during use	• Implement default power-down when systems are not in use. • Use feedback methods to indicate how much energy or water are being consumed. • Implement intuitive controls for resource-saving features.
	Appropriate durability	• Ensure the aesthetic life is equal to the technical life. • Facilitate repair and upgrading. • Ensure minimal maintenance. • Minimize failure modes.
Recovery	Disassembly, separation, and purification	• Ensure that joints and fasteners are easily accessible. • Ensure that incompatible materials and parts are easily separated.

Petala et al. [30] explore barriers and organizational issues to integrating sustainability targets in new product development, using Uniliver as a case study. The study concludes by stating that organizations need to communicate clearly to project teams and senior management their sustainability development goals and their importance, as well as emphasize the need for cross-functional teamwork during the product development process in order to integrate sustainability. Moreover, the research highlights there is a gap between sustainability tool development and their use and implementation; the importance does not lie in developing the sustainability tool, but rather in how it will be implemented in the innovation process. Finally, the work concludes by stating integration of sustainability into the new product development process does not guarantee results due to several other organizational issues. Maxwell et al. [31] describe a framework and method for implementing sustainable product and/or service development through the entire lifecycle of a product or service that identifies and assesses options that may be implemented to optimize sustainability. They consider impacts on functionality, environmental and social impact from raw materials, production and distribution, consumption, and end of life. They also consider economic impacts of all phases and conclude by stating early testing of the methodology indicates it is effective and a “WIN-WIN” situation for businesses and for sustainability benefits in the supply chain. Schoggl et al. [32] provide a checklist for sustainable product design specifically for the automotive industry. The checklist includes nine categories: resource efficiency, resource consumption, use of low-impact materials, optimization of end of life phase, health and safety aspects, transport and logistics, social and ethical aspects, decrease of environmental pollution, and economic efficiency and profitability. Hallstedt [33] provides an approach to identify sustainability criteria and present them in a set of matrices for every product life-cycle phase and add a qualitative measurement scale for the criteria to be used in the early product development process. Finkbeiner et al. [34] address the challenge of measuring and evaluating the social and economic dimension of integrating sustainability performance into a product or process for a business. Finally, a literature review of 114 scientific articles related to ecological sustainable entrepreneurship, or sustainable business, is conducted by Gast et al [35]. Their work highlights how fragmented the sustainable research field is and proposes an integrated framework to help future research.

These studies clearly indicate there are multiple approaches to integrate sustainability into the design process and multiple indicators to use to evaluate the sustainability of a product. This makes it difficult to understand what approach is optimal to use and adds more decisions to make throughout the product development process. Often these decisions have trade-offs, further complicating the process to make decisions in a timely manner. Moreover, the work highlights the need for collaboration and creating tools that integrate into the product design and development process to help inform sustainability choices.

In addition, the research presented focuses on using LCA and DFE approaches for the product development process and concentrates on the overall sustainability of the product. An emphasis on material sustainability is made only when referring to reducing the amount of material used and reducing its processing and manufacturing energy use, and finally looking at its end of life options. Yet there are research studies and initiatives that more specifically address material sustainability, as discussed below.

Sustainable Materials

Other efforts have concentrated solely on research about and use of sustainable materials. The United States Environmental Protection Agency has built a roadmap for sustainable materials management by 2020 [1]. They recommend using a life cycle materials management approach by looking at materials through their life cycle in order to study the material’s environmental impact. This approach is similar to the LCA approach discussed above, yet the emphasis is placed on the material’s life cycle rather than the product’s life cycle. They also define more stages within the lifecycle process that include extraction, transportation, processing, distribution, consumption and end of life. The EPA also recommends minimizing the amount of material used, reusing materials and reducing waste, as well as promoting environmentally preferable products.

Other research such as Krausmann et al. [36] and Giljum et al. [37] has concentrated on material flow analysis. They argue that the growing demand for raw materials and the processes they undergo result in waste and emissions that are affecting global sustainability and environmental health. They map historical material extraction and use till now and discuss implications for sustainable development. Specifically, Giljum et al. address fossil fuel consumption and its connection to climate change and the link between biomass consumption and water scarcity whereas Krausmann et al. study material groups related to biomass, fossil energy carriers, ores and non-metallic minerals for industrial use, and construction use. The papers link their material consumption findings to population growth, material productivity and intensity, and GDP. One overarching conclusion is that material consumption rates have surpassed population growth rates. Allwood [38] recommends optimizing designs to use less material, reducing yield losses, diverting manufacturing scrap to smaller manufacturers that need and use less material, reusing components before recycling them, extending the lives of products and reducing final demand. Finally, Helbig et al. [39] discuss the benefit of resource strategy to reduce supply risk and enhance environmental sustainability by studying a materials value chain, risk within the value chain including geographical localization, and aggregate 12 indicators. Other methods used to evaluate materials will be discussed later.

As can be seen, material sustainability recommendations are similar to the broader product development guidelines. They place more emphasis on material LCA, material use reduction and extension of their life for reuse or recyclability yet they do not discuss how to make these materials choice decisions.

Safer Chemicals in Materials and Products

At the most basic level of chemical use, efforts have been made by governments, NGOs, product manufacturers, and retailers to use safer chemicals in materials and products. Chemicals have hazards that are intrinsic to their molecular structure that cannot be eliminated. Thus, even at low exposures, some chemicals have harmful effects to human health and the environment. In the United States, four laws exist that require the reporting of chemical information [40]:

> The Toxic Substances Control Act (TSCA) was issued in 1976 to regulate new or already existing chemicals and chemical mixtures that present unreasonable risk to human health and the environment. It requires testing, record keeping, and reporting of chemicals, and can restrict or prohibit their manufacturing, use, distribution or disposal [41]. It excludes, however, substances in food, drugs, cosmetics and pesticides.
>
> The Federal Food Drugs and Cosmetics Act (FFDCA), establishes the framework in which the US Food and Drug Administration (FDA) operates, and requires the scientific and regulatory evaluation of new drugs, food additives, and coloring agents, as well as authorizes levels of pesticides and additives on or in food products, and establishes standards for chemical content in products [42].
>
> The Consumer Products Safety Act (CPSA) established the Consumer Products Safety Commission (CPSC) that require labeling of hazardous household products that may cause health hazards and have passed voluntary and mandatory standards for consumer products [43].

> The Federal Insecticide, Fungicide, Rodenticide Act (FIFRA) regulates the distribution, sale, and use of pesticides and requires testing and registration to prevent adverse effects on the human health and the environment [44].

In 2006, the European Union passed REACH, a new policy to manage chemicals on the market. It requires companies to register, evaluate and test their chemicals for hazards and obtain government authorization to use chemicals with high concern [45]. It places the responsibility on the firms manufacturing and using chemicals and is now an international standard. Yet, over 30,000[2] chemical substances are used in industry [43], and therefore even with these laws and policies, it has been impossible to study the effects of all the chemicals being used in products.

State laws have developed in order to address some of the chemical hazard gaps. The two most prominent laws are California's Safe Drinking Water and Toxic Enforcement Act of 1986 (also known as Proposition 65) and the Massachusetts Toxics Use Reduction Act (TURA). Proposition 65 was published by the Office of Environmental Health Hazard Assessment (OEHHA) and requires the labeling of chemicals known to cause cancer, birth defects or other reproductive toxicity [46]. It is updated annually and started with 65 chemicals known to cause harm and is now at almost 1000 substances. TURA requires companies in Massachusetts who use toxic chemicals in large quantities to develop a plan for eliminating or reducing pollution and measure and report their results annually [47].

These federal and state efforts have resulted in the removal of mercury and lead, both poisonous chemicals from products such as medical devices, paint and toys. Moreover, they have resulted in the required labeling of hazardous chemicals in products such as flame retardants in furniture, formaldehydes in air fresheners, parabens in cosmetics, and bisphenol A in water bottles. This is just a small example of the everyday products that people are exposed to that contain harmful chemicals. Product manufacturers are also playing a role to push the use of safer chemicals. They have created restricted substance lists for the apparel, electronics, automotive industries such as the American Apparel and Footwear Association Restricted Substance List, the Join Industry Guide, and the Global Automotive Declarable Substance List respectively.

Moreover, product manufacturers such as Nike, Levi Strauss, Hewlett Packard, and Method are striving to select safer chemicals in their products yet their approaches are fragmented from each other due to confidentiality [43]. Finally, retailers such as Walmart and Staples are also launching programs for safer chemical selection yet are also limited due to lack of data disclosure from their supply chains. These attempts have resulted in a limited impact throughout industries. More information about the push for safer chemicals will be addressed in Chapter 4 and Chapter 7.

It is important to note, chemical manufacturing industries are also trying to address sustainability related to the chemicals they manufacture. Martins et al. present a framework for sustainability metrics applicable to chemical industrial processes [48]. They evaluate the three pillars of

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[2] Although different numbers were cited earlier for the number of chemical substances that exist, this number was cited from Geiser's book, Chemicals without Harm [43], which focuses on chemicals and chemical policy.

sustainability and propose four metrics: material intensity, energy intensity, potential chemical risk to the human health, and potential environmental impact.

Even with the government laws in place, as highlighted above, they cannot cover all aspects of producing and consuming safer chemicals and how they are feeding into materials and products. Moreover, the difference between government, state, and international laws highlights the complexity within the regulatory environment. Since REACH shifts the burden of evaluating hazards of chemicals from the government to the manufacturers, it is shifting the dynamics for developers from eliminating hazardous chemicals to creating and using safer chemicals. Industries have been trying to join the efforts to fill in the gaps by creating their own sustainable material databases yet their influence is limited. These initiatives show there is a growing need to define what materials are sustainable and help choose sustainable materials for products before or during their development.

1.5 Where this Research Fits

This short summary of the work that is already being done on materials selection for sustainable outcomes shows a number of gaps. There is no question that there is growing momentum driven both by regulatory requirements and by industry-based initiatives for use of safer chemicals and materials in product design and development. Generally, however, based on this research the designers and engineers who are to implement these choices are simply given a “red list”, a list of materials or chemicals that cannot be used, but little guidance for choosing among the materials or chemicals that are not on that list.

Furthermore, while the product design and materials choices approaches reported in this chapter concentrate on measuring sustainability impacts in products and materials and address strategies to design sustainable products, they do not state how these strategies fit into the development process workflow. Moreover, use of multiple of the methods described can result in different conclusions. Finally, the trade-offs that designers and engineers must make among economic, social and environmental sustainability in making materials choices have not been thoroughly explored. This research aims to fill in missing details to simplify and map the sustainable decisions to be made by engineers and designers, thus pushing material sustainability and product sustainability forward in order to conserve the ecosystem for future generations to come.

1.6 Dissertation Structure

The sustainable performance of products depends on the choices of materials that go into those products. This research seeks ways in which sustainable performance might become a more integral part of the materials choice process, specifically in the 3D printing industry.

It focuses first on understanding how designers and engineers make material decisions and evaluating the complexities associated with multiple health and environmental impacts of specific 3D printing materials. Moreover, designers and engineers are often pressed to make quick decisions, and the complexities of evaluating environmental options make it anything but quick. The research aims to more simply map the trade-offs to be made among costs, performance and environmental impact, and use an iterative design process in order to facilitate better material decision making. Ultimately, this research addresses why sustainable material decisions are not well integrated into the product development process and highlights the significant barriers to overcome in order to do so. A tool was built that gathered material data and resulted in a set of specifications for how a tool should work to address material sustainability in the future. A more detailed description of the remaining structure of this dissertation is outlined below.

- **Chapter 2** draws data from user interviews. This chapter focuses on how industries approach the product development and material selection process. Commonalities and differences between the material selection processes are highlighted as well as sustainability thinking. This chapter concludes with what aspects in the material selection process are important when making material decisions, where materials choices fall in the product development process, and highlights the complex interactions among sustainability, performance, and profit
- **Chapter 3** describes the additive manufacturing industry and focuses on 3D printing technologies and materials.
- **Chapter 4** highlights the standards and regulations related to the additive manufacturing industry as well as existing databases, frameworks and tools that can be used to address material sustainability in any industry. It then dives into research done to address the sustainability of 3D printing and concludes by drawing data from more focused interviews with users in the 3D printing industry.
- **Chapter 5** reviews the material data collection process. It identifies the 3D printing materials, their performance properties, printing properties, aesthetics, costs and regulations as well as their hazard properties. The chapter concludes by focusing on the lessons learned from the material data collection and why it is difficult to integrate sustainability into the material decision making process.
- **Chapter 6** explains how the material selection tool was created and lessons learned on important tool specifications that should be included on a future tool in order inform more sustainable material selection.
- **Chapter 7** concludes the dissertation and highlights the contributions from this research and provides recommendations on how continue this research using a systems perspective, how industry should fill remaining material gaps, how to update and expand the tool, how to influence the supply chains to comply, and how leadership can further encourage businesses to adopt material sustainability practices.
- **Appendix** consists of the background data and information collected for this dissertation.

Chapter 2

Empirical Studies

In order to gain insight into the current methods of material selection done in industry, a series of interviews were conducted. The objective of the interviews was to gather data across different industries and different job positions to determine how material choices are made in practice, what materials characteristics are important, what regulatory standards or guidelines are most applied, what tools are used, and what might facilitate the material decision making process easier and more effective in the future. The diversity of industries and positions of the interviewees were used to examine how the material decision making process varies between sectors and where commonalities exist.

The chapter opens with a description of the interview research, who was interviewed and what questions were asked. It then describes the findings from the interview research around language, tools and methods used, where materials choices fall in the product development process, and what kinds of tradeoffs are made in the process. It also identifies where there are commonalities and differences among industries or companies.

2.1 Interviews

The interviews were carried out either over the phone or in person. Interview guidelines, methods and approaches, such as Constable et al. [49] and Weiss [50], were used in order to insure the interviews were effective. The first step of the interview process was to address any confidentiality dilemmas that the interviewee might have and agree on reporting guidelines.

Each interview consisted of a sequence of 19 questions that were divided into two segments. The first segment asked questions about the interviewee's career to capture background information on their experience with materials selection, while the second set of questions were specific to the design and material selection process. Following the protocol of ethnographic interviewing, the questions were open ended to allow interviewees the most freedom in addressing the questions, and not overly influence their answers. A list of the questions used during the interviews can be found in Appendix A2.

A total of 27 interviews were conducted. Of these, 7 individuals worked in the electronics industry, 4 in the manufacturing industry, 5 in the medical industry, 3 in the software industry and 8 in assorted other industries. Moreover, 7 individuals were product managers, 5 were product design engineers, 2 were material engineers, 2 were mechanical engineers, 4 were designers and 7 held other job titles. Table 2.1 summarizes each interviewee's general industry affiliation, the specific space within the industry their company operates in, their job title, and the date and location of each interview.

Table 2. 1 Interview summary

Name	Industry	Space	Job Title	Date	Interview Type
A	Consumer Electronics Technology	Consumer Electronics	Product Design Engineer	19-Apr-16	Phone call
B	Consumer Electronics Technology		Materials Engineer	21-Apr-16	Phone call
C	Design Consulting	Food Packaging	Materials and Manufacturing Engineer/ Specializing in package design and development	4-May-16	Office Visit
D	Design Consulting		Product designer & mechanical engineer	1-Jun-16	Phone call
E	Electronics Design	Consumer Electronics	Development Engineer	26-Apr-16	Office Visit
F	Electronics Design	Consumer Electronics	Product Designer	26-Apr-16	Office Visit
G	Electronics Design	Consumer Electronics	Industrial Designer	26-Apr-16	Office Visit
H	Electronics Design	Consumer Electronics	Industrial Design Manager	26-Apr-16	Office Visit
I	Electronics Material Supplier		Senior Product Manager	2-May-16	Phone call
J	Fiber Optic Market	Design and Manufacturer	Senior Product Line Director	20-Apr-16	Meeting at Berkeley
K	Food & Beverage		Senior Manager, Materials Technology	13-May-16	Phone call
L	Innovation and Enterprenuership Space		Manager/ Inventor/ Engineer/ Designer	23-May-16	Phone call
M	Manufacturing	Designer and Manufacturer of Access Equipment	Product Manager	18-Apr-16	Meeting at Berkeley
N	Manufacturing	Food safety devices	Senior Product Manager	20-Apr-16	Phone call
O	Manufacturing	Bicycles	Business Solution Manager	21-Apr-16	Meeting at Berkeley
P	Manufacturing	Machine Tools	Senior Mechanical Engineer/ Machine Design Team	27-Apr-16	Office Visit
Q	Medical	Single use disposable medical products	Marketing Analyst	19-Apr-16	Meeting at Berkeley
R	Medical	Single use disposable medical products	Product Manager	19-Apr-16	Meeting at Berkeley
S	Medical	Single use disposable medical products	Product Manager	19-Apr-16	Meeting at Berkeley
T	Medical	Surgical tables and accessories	Senior Engineer, New Product Introduction	20-Apr-16	Phone call
U	Medical	Surgical Instruments	Mechanical Design Engineer	25-Apr-16	Phone call
V	Mobile Technology	Chips/ semiconductors	Director, Product Management	18-Apr-16	Meeting at Berkeley
W	Power Management Company		Divisonal Program Manager	19-Apr-16	Phone call
X	Software Corporation		Design Engineer, Strategy and Research/ Product Development Group	28-Apr-16	Phone call
Y	Software Corporation		Senior Sustainable Design Program Manager	4-May-16	Office Visit
Z	Software Corporation		Product Manager/ Digital Manufacturing Group	12-May-16	Office Visit
AA	Wearable Technology	Consumer Electronics	VP, Industrial Design	26-Apr-16	Office Visit

As can be seen, four companies above are listed under the manufacturing industry although their work can also be categorized in the industry their space describes. The reason they are listed under manufacturing instead of their space, is because these companies manufacture their products in house. Other companies listed above propose designs or consult on products that then feed into the manufacturing industry as well. These companies may prototype in house, yet their final products are given to a third-party manufacturer to produce. In addition, people from software corporations were interviewed to learn how they customize, build and integrate their software for their users. An emphasis was placed on how the software can fit into the user workflow in order to be adapted. Moreover, some of the software they create focus on material selection.

2.2 Results

As stated before, interviews were conducted in order to gain a deeper insight into how material decisions are made in industry. When possible, the interviews were recorded, yet in all cases notes were taken. After each interview, the notes were further organized into an excel file. The notes taken from each interview were divided into different sections, depending on what the interviewee was describing. The sections included important characteristics under consideration when making material decisions; what tools or libraries are used; regulations that affect their work, product, or industry; how final material decisions are made if a conflict arises; where does sustainability play a role in their work; and what would facilitate the material decision making process. In each one of these sections, examples and quotes that the interviewee stated was also captured. In addition, there was one more section with other comments that addressed useful information that was expressed. Organizing the captured data facilitated the process to learn more about the common characteristics used in industry to make material decisions, how material decisions are made, what tools or libraries are used, and finally what is missing or what would facilitate the decision-making process for a range of industries. Below is a summary of the findings.

Common Characteristics

Analysis of the interviews showed that materials decisions are generally based on a set of characteristics. Collectively, across all industries studied, the most common of these are costs, performance, and aesthetics of the final products. Yet, the order of importance and the metrics used to define each of these characteristics differ between industries.

Cost was cited as one of the major drivers for material selection in all of the 27 interviews conducted, as lowered costs allows for lowering the overall price of the product being produced. As one interviewee noted:

Pricing is driving business. – Product Manager; Manufacturing

Costs related to material decisions are just the costs of the materials themselves. Yet there are other costs associated with the materials throughout the product development process such material processing costs and manufacturing costs. Often, the material processing costs are incurred by the actual material supplier in order to transform the raw materials into the final finished material goods for sale. The material manufacturing costs are related to transforming the material into a finished part or product and thus is incurred by the business developing the final product.

Performance characteristics ranged between mechanical properties and functionality. Frequently cited mechanical properties that influence material decisions included the strength and weight of the material, and its ability to withstand stress and loading fatigue, meet critical tolerances, and meet thermal and manufacturing requirements. Functionality included the material's ability to meet the products' intended use and maintain its quality while remaining safe and reliable. In addition to the functionality constraints, the materials must meet the safety and regulatory requirements set by the respective industry.

Finally, according to the interviews, the last common characteristic that material decisions are based is aesthetics. Aesthetics of the products relate to the look, feel, touch, shape, and color of the material and consequently of the final product. In parallel with material design choices, designers often create mood boards by gathering inspirational images, trends in industry, and visual feelings and observations to immerse themselves in the product and innovate on its aesthetic. Designers cited this characteristic to be important because it determines how customers will react to the final product, what image and trend the product will create, and who will want to buy and own it. Aesthetics concerns are much higher for the consumer product industries than others.

Table 2.2 summarizes the three most commonly cited criteria used for making materials choices along with the descriptions and properties they represent. To remain consistent throughout the paper, the terminology – performance, aesthetics and cost -- will be used to represent the sub-criteria as well.

Table 2. 2 Terminology of material category descriptions

Performance	Aesthetics	Cost
Mechanical properties; functionality; reliability; safety; quality	Color; finish; feel; opacity; reflectivity	Materials; processing; manufacturing

Decision Making

Although cost, performance and aesthetics were broadly shared criteria across industries, not all industries value their importance in the same order and not all three characteristics are universally used. In fact, collectively, the interviews suggest there is not a single universally adopted approach to choosing materials. As one interview noted,

> *Material selection is the most broken aspect in design. –Product Design Engineer; Consumer Electronics*

Decision making happens in various stages throughout the design process and by different teams. There was no overlap between industries or positions on the order of operations or management of material decision making. The list below captures the primary modes described by interviewees for selecting materials.

1. After the product requirements are set by the leadership team and the mechanical properties are specified by the engineering team, the supplier is then requested to source the material needed to meet the specific criteria. – Materials Engineer; Consumer Electronics Technology
2. The engineering team makes the final material decisions. Product Management Director; Mobile Technology and Senior Product Line Director; Design and Manufacturer
3. The engineering team recommends the material and their recommendation passes through the leadership team to make the final material decision. The leadership team varies from company to company and could be the lead engineer, the manager of the project, or even the executive team at the corporate headquarters. Product Manager; Manufacturing
4. The engineering team's material decisions passes through the financial team to evaluate if it meets their gross profit margins and if their retail price matches the consumer price point of competing products. If it passes, then the design and material selection gets approved, if not, it returns to the engineering team for other options. – Business Solution Manager; Manufacturing
5. Designers are encouraged to prototype their designs using any material on hand and propose materials for the final product, yet that does not dictate that the material will be used. Once the final design is chosen and tasked to the manufacturing engineers, the manufacturing engineers will make the final material decisions that will fulfill the functionality and design of the product. – Industrial Designer; Electronics Design
6. Material decisions are based on their national market availability, regulatory and/or internal standards, and/or a limited selection of materials that are approved for use in their industry. - Electronics Material Supplier; Food & Beverage; Medical

Generally, if no materials choice consensus can be reached within a team, either a group discussion occurs where evaluation metrics are ranked according to importance and thus the material is scored against other options, or the individual in charge makes the final decision. Some interviewees stated the lower cost material is almost always chosen.

The variety in approaches to materials choice makes it particularly difficult to create models that can be applied universally, and thus limit the ability to embed sustainable choice-making in the process.

Tools and Material Libraries

Nearly all the interviews stated that no material library or tools are used to view and evaluate a list of material possibilities for their application. Part of the reason for this is another interesting commonality that emerged from the interviews: designers and engineers tend to stick to the materials they are familiar with and have used in the past. Once a material has previously proven to meet the set of performance property requirements, little more investigation and research is done. This leaves little room for innovation. Multiple interviewees articulated this general rule as can be seen below.

99% of the materials are already decided on unless there is a need to change it;
Don't change it if you don't have to. – Product Design Engineer; Consumer Electronics
If it ain't broke, don't fix it. – Development Engineer; Electronics Design
Only make changes to respond to customer needs or push. –Senior Product Manager; Manufacturing

These materials are called grandfathered materials since they are proven to meet their needs and are most commonly used. When the grandfathered materials do not meet desired specifications, then either the material supplier is contacted to recommend a material that will meet their needs or a Google search is performed for new possibilities and/or a list of certified materials from their respective industry is used. Such certified materials list often follow a regulatory policy discussed in Chapter 4. As one interviewee from the consumer electronics industry stated,

RoHS is the biggest driver to material selection today. – Industrial Designer; Consumer Electronics

Design companies also stated that they follow a Color, Material, Finish (CMF) catalogue of materials in order to monitor what is currently trending. Yet the final material choice is based on the material performance properties, including quality and safety (Table 2.2), and costs.

Only one company out of the 27 interviewed performs a life cycle assessment (LCA) yet stated that they did not necessarily understand the impact metrics of the results. Other interviewees were aware of what an LCA was but did not perform the analysis at their company. Finally, one interviewee stated they do not perform an LCA but do try to minimize their material usage in order to minimize their environmental impact.

In summary, the companies interviewed generally use "grandfathered materials" when they can. When they cannot, they are selecting materials based on cost, performance, and sometimes aesthetics considerations. Final materials choices may be made by a variety of players in the organization, generally from design, engineering or management. And, very few if any tools or materials lists are used. This sets up a considerable challenge for imagining how sustainability considerations might be made in the materials selection process.

Sustainability in the Decision-Making Process

It is important to note that throughout the interviews, sustainability was not an important characteristic in making material choices. Many interviewees stated that is it hard to track the hazards and sustainability of their material choices throughout their supply chain. The predominant argument was that although they care about it as individuals, a company does not have the financial resources and time to invest in determining the human health and environmental hazard effects of their decisions.

Material decisions are often made under quick time constraints and designers are encouraged to innovate on designs, not materials. If a company were to outsource these sustainability evaluations and perform, for example, an LCA, it would cost anywhere between $10,000 to $60,000 and take up to three months to complete [51], and a hazard assessment can cost $1500 per chemical [52]. Thus, as long as the customers do not demand a change in sustainability performance, companies aim simply to meet performance and costs objectives.

Many interviewees believed that sustainability is only valued if it is part of a company's core values and branding. Otherwise, they believed, it could be used as a good publicity story if it in fact did reduce costs and increase profits of a company.

"Sustainability is important but not a main concern" Product Management Director; Mobile Technology
"Corporate is not worried about material sustainability; Innovate on details of a product, not materials" Industrial Designer; Electronics Design
"Sustainability and environmental considerations are usually tied to a brand." VP Industrial Design; Wearable Technology
"There are two reasons to choose sustainability: branding and financial implications and savings." Design Engineer; Software Corporation

The other predominant complaint about integrating sustainability into the decision-making process, besides time and cost constraints, is that there are no metrics to quantify the value of sustainability to the planet and to the business. LCA tools were criticized because they output a number or score but do not address how this number was calculated, what the qualitative effect will be, and what is realistically achievable for a company. Moreover, an LCA does not address financial business impacts such as how the customer acceptance of the product will change if sustainability was integrated.

When asked what barriers exist to integrate sustainability into the decision-making process, a majority of the interviewees responded that the greatest barrier is the lack of understanding by engineers, manufacturers, and designers on the issues related to material sustainability and awareness of the waste their products are creating. Other barriers included resistance to change the work process that is currently used and difficulty to complete the paperwork required to bring a change to a company's work standards. One company explained that expertise comes and goes, thus an attempt to build a database of material sustainability would be difficult to keep up to date due to incoherent data that would only makes sense to the creator.

Lastly, when asked what would facilitate the decision-making process and help integrate sustainability, multiple interviewees explained that a library that contains the mechanical properties, environmental concerns, and costs of materials all in one place does not exist and would be useful. Currently, this information must be drawn from multiple sources and information is not consistent across those sources. Moreover, integrating regulations and standards that highlight what materials are non-toxic and can be used in a specific industry would further aid the process. Other interviewees stated they would like to have multiple search options within a database while manufacturers said they would like to connect a library to the impacts on large scale manufacturing. Some respondents noted that testing a prototype with new materials is often difficult due to unknown properties and uncertainties with scaling from a prototype to a full product. Finally, others indicated that if tools could be used for rough feedback to help understand and elevate sustainable practices, then they are more likely to be used.

The feedback from the users indicate there is an awareness around sustainability and would like to integrate into their product development process yet no library or tool exists that combines sustainability data with costs, mechanical properties and industry regulations. Moreover, there is a need to understand the impacts linked to materials choices in order to encourage a company to address material impacts in their products. A solution should integrate these core functions.

2.3 Product Development Flowsheet

The generic product development process is taught in product design and development books as a sequence of steps that an organization should follow in order to design and generate a final product. As can be seen in Figure 2.1, it is broken into 6 phases with the tasks and responsibilities highlighted for each phase. The phases include planning, concept development, system-level design, detail design, testing and refinement, and production. Yet this depiction is not accurate with industry practice as the interviewees for this research describe it.

	0. Planning	1. Concept Development	2. System-Level Design	3. Detail Design	4. Testing and Refinement	5. Production Ramp-Up
Marketing	• Identify market opportunity. • Define market segments.	• Gather customer needs. • Identify lead users. • Identify competitive products.	• Develop plan for product options.	• Develop marketing plan.	• Develop promotion and launch materials. • Test in field.	• Distribute early production with key customers.
Design	• Consider product platform and architecture. • Assess new technologies.	• Investigate feasbility of product concepts. • Developl industrial design concepts. • Build and test experimental prototypes.	• Develop product design. • Define major sub-systems and interfaces. • Refine design. • Preliminary component engineering.	• Define part geometry. • Choose materials. • Assign tolerances. • Complete industrial design control documentation.	• Test performance, reliability, and durability. • Obtain regulatory approvals. • Assess environmental impact. Implement design changes.	• Evaluate early production output.
Manufacturing	• Identify production constraints. • Set supply chain strategy.	• Estimate manufacturing cost. • Evaluate production feasibility.	• Identify suppliers for components. Perform analysis to buy or make parts. • Specify final assembly scheme.	• Define piece-part production processes. • Design tooling. • Define quality assurance processes. • Procure long-lead time tooling.	• Facilitate supplier ramp-up. • Refine production and assembly processes. • Train workforce. • Refine quality assurance processes.	• Begin full operation of production systems.
Other Functions	• *Research*: Demonstrate available technologies. • *Finance*: Provide planning goals. • *General Management*: Allocate project resources.	• *Finance:* Conduct economic analysis. • *Legal:* Investigate patent matters.			• *Sales:* Develop sales plan.	• *General Management:* Reflect and review project after completion.

Figure 2. 1 Product design process, adapted from Ulrich and Eppinger [6]

In the generic process, material selection does not occur until Phase 3 where it is done by the design team. Moreover, it is simplified to "Choose Materials" followed by "Assign tolerances" and "Obtain regulatory approvals" in phase 4. According to the interviewees, choosing materials is a more complex process that involves assigning the critical components such as tolerances and performance requirements first and then choosing between materials that also meet regulatory requirements. Meeting regulatory requirements before the testing and refinement phase is important since a company does not want to invest their time and effort into a product that will not be able to go to market. Moreover, in addition to meeting regulatory requirements, material choice is often based on materials previously known to work and costs, neither of which is addressed in the generic process.

Finally, this process does not address the decisions the management team makes regarding the market opportunity and during the concept development and design detail phases throughout the design process and the financial implications that should be considered during the process. It simply lists a few management and finance responsibilities under "Other functions", yet does not integrate them into the process.

Figure 2.2 highlights how material decisions are done in industry according to the interviews that were conducted for this research. First, the strategy that addresses the needs and requirements of the market is established. This strategy then feeds into the product development team who will study the parameters and critical components and performance issues in order to propose and prototype a design. The design then goes to the management team for their approval and gets passed to operations management and engineers to look at its feasibility for production. The operations management and engineers also interact with the manufacturing facility to see if the design can be manufactured. If adjustments need to be made, the design will go back to the design team until a final design is agreed upon. Once the design is finalized, the operations management and engineering team will look into grandfathered materials known to work for the purpose of the product. Often, the manufacturing facility also proposes materials that may be used. If the materials meet regulations and product requirements, a bill of material, manufacturing process and timeline are then created and passed onto the management team to finalize and determine if they meet their financial and business strategy. Once approved, the final design is sent to the manufacturing facility for production. The manufacturing facility and safety department work closely together in order to ensure equipment and material procurement, installation and manufacturing safety processes are being met. The final product is then produced and ready to go to market.

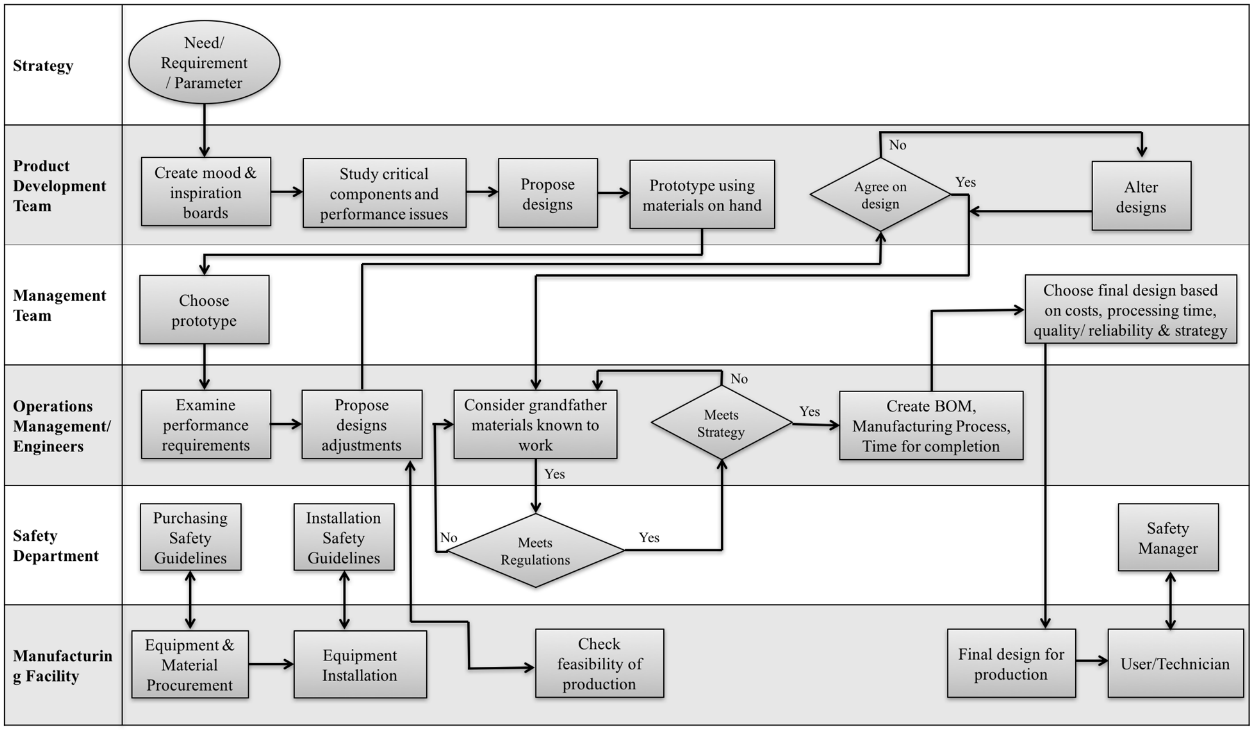

Figure 2. 2 Product development process

As can be seen, in reality there is more complexity involved during the design process than textbook models highlight. Although textbook models emphasize the need for iteration during the design process, which is important in reality as well, they do not capture the importance of the interactions between the players involved during the design process. Each stage of the product development phases is not complete by the individual players responsible for the phase, rather constraints come from other teams and everyone needs to work together to reach a decision that will benefit the product. The design team interacts closely with the operations management/engineers' team in order to make sure their design meets the performance requirements and is technically feasible, the operations management/engineers team closely interact with both the management team to check that the proposed product meets their strategy and goals, and with the manufacturing facility to make sure the product can be made as specified.

2.4 Integrating Sustainability into the Material Decision-Making Process

This chapter, reporting on empirical research on how materials choices are made in industry today, has made clear so far that sustainability considerations are rarely made – beyond compliance with regulations – in product design and development. Instead, cost and performance are the primary drivers for materials choices. Even worse, as indicated by some of the interviewees, sustainability is seen as requiring a trade-off with performance and cost. As most of the interviews implied, sustainability is best used as a branding tool and will not be integrated into the design process unless it is tied to financial savings.

One company that not only believes in sustainable design, but is a leader in their industry and is only using safer materials in their products, although not required, stated that they are not advertising their products any differently than they used to before they started using safer materials. The reason they stated was that they do not want to emphasize and label their product special or “green.” The company revealed that if their products are labeled differently, it will break the emotional connection between the product and their customers, making them feel that the new green product is now only for a certain type of customer or certain look. Moreover, they revealed that the customers are more likely to think it is more expensive and avoid their product.

The interviews highlighted the complex interactions among sustainability, performance, and profit depicted at a high level in Figure 2.3.

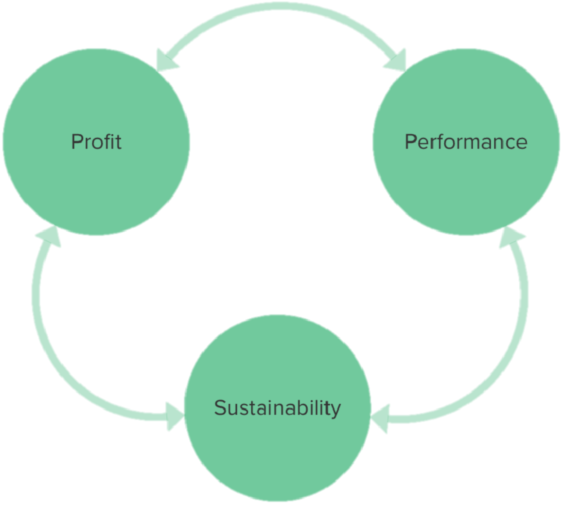

Figure 2. 3 Sustainability, profit and performance interactions

Figure 2.4 provides a more detailed depiction of the complex trade-offs companies must make among these three variables. It explains a commonly shared view of the effect of investments in sustainability on profit and performance. When the goal of a company is to increase the sustainability of their products, they often increase pressure on their supply chain in order to source more sustainable material. Yet a negative connotation exists, where an increase in material sustainability thus leads to poorer performance. If the performance of a product decreases, then the company might consider redesigning their product. This may then lead to less customer satisfaction due to the change in product, decreasing revenues and thus decreasing profits. If the company does not redesign their product and keeps it with the decreased performance, customer satisfaction will also decrease, having the same negative effect. Moreover, increasing material sustainability leads to an increase in material costs. To make up for the increase, a company may increase their product price point thus again leading to a decrease in customer satisfaction, revenue and profit.

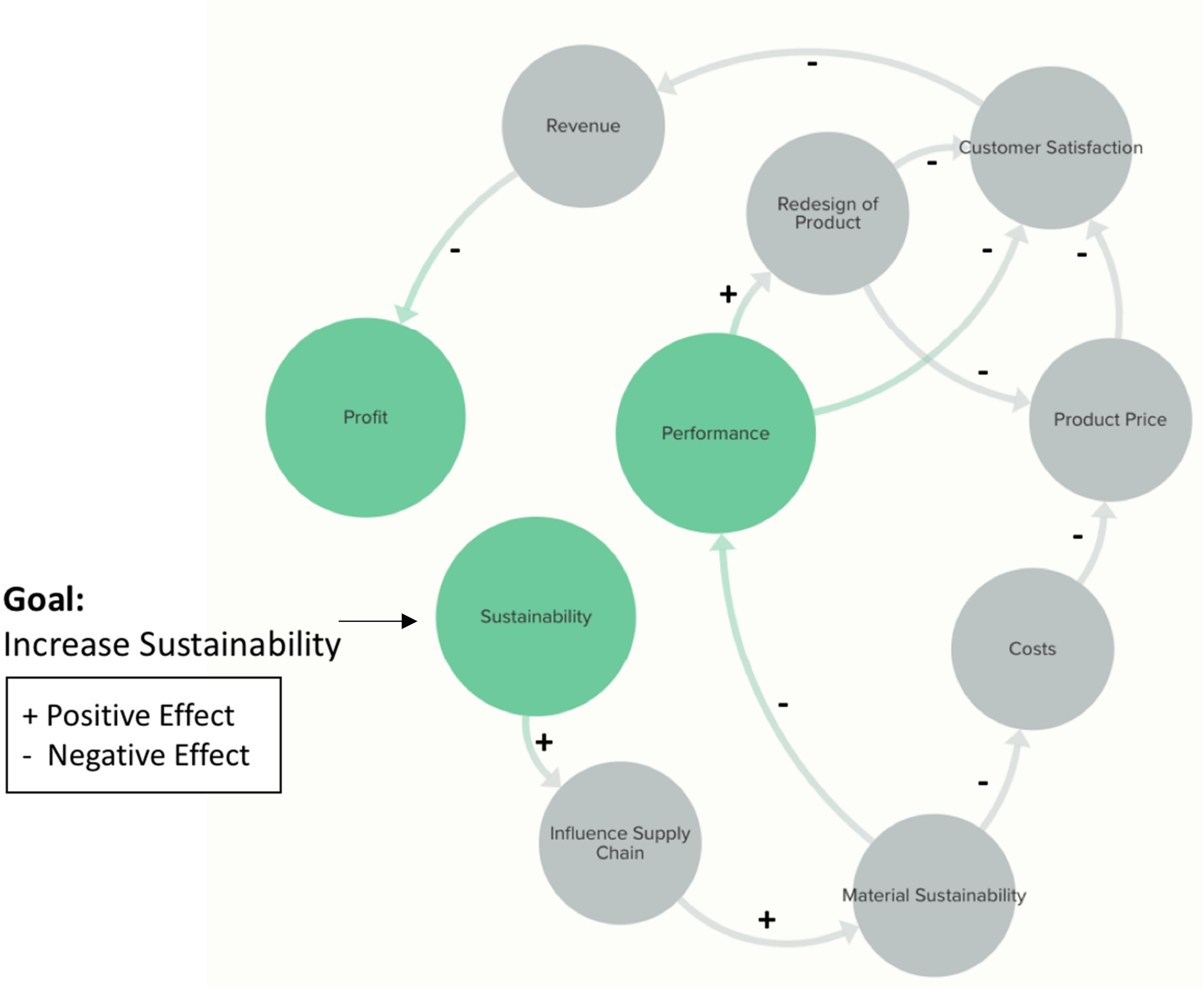

Figure 2. 4 Effect of sustainability on performance and profit

Yet, Figure 2.4 does not objectively depict the effect of sustainability on performance and profit. Although the dynamics described may occur, it is not always the case as Levi Strauss & Co. and other industries have been proving (discussed in Chapter 7). Sustainability choices must consider the effect on the triple bottom line: environmental, economic and social impacts. Economic effects are not only short term cost reductions and revenue growth, but also include long term growth and development of customer loyalty. The implementation of improved environmental performance, for example, might boost a company's image and increase customer satisfaction and thus increase revenue and profit [53]. Moreover, better sustainable practices may decrease operating costs by increasing resource efficiency thus increasing revenue [53]. More sustainable material may last longer and therefore decrease material use over product life cycles and increase lifetime performance of the product.

As argued in Chapter 1, integrating material sustainability into the design process is crucial since it will not only affect the final product but also how it will interact with the environment and society. Chapter 2 shows the complexity of doing so given current practice. It acknowledges the difficulties of getting the right data to the right people at the right place in the process. This research aims to more simply map the trade-offs to be made among costs, performance and sustainability impacts, and use an iterative design process in order to facilitate better material decision making.

Chapter 3

Additive Manufacturing Technologies and Materials

In order to map the trade-offs to be made among costs, performance and sustainability impacts in the design process, a case study was used as an example to understand how integrating these metrics can facilitate better material decision making. Specifically, 3D printing materials were used for the case study due to the growing use of 3D printing technology. The information presented in this chapter highlights the importance of additive manufacturing and the growth of additive manufacturing technologies. The chapter then dives deeper to understand the different 3D printing technologies and their sustainability implications.

3.1 Manufacturing

"Manufacturing is the processes [or art/science/technology] of converting raw materials into products [54]." Manufacturing is important because it accounts for 9% of the US workforce and would be the ninth-largest economy in the world. In 2015, manufacturing contributed \$2.17 trillion to the U.S. economy and it was estimated that for every \$1 spent in manufacturing, \$1.81 was added to the economy [55]. Moreover, manufacturing enables research and development, contributing to more innovation in industry.

The historical development of materials and manufacturing process can be dated back to 5000-4000 B.C. [54]. The historical driver of manufacturing is connected to the production of household items, otherwise known as craft production. Over time, manufacturing technologies developed into more sophisticated processes and equipment in order to meet consumer needs and continuously evolved. The shifts in manufacturing and their enabling technologies for each paradigm can be seen in Figure 3.1. Initially, man only created one craft at a time by hand according to their needs, such as hunting tools and knives [56]. As craftsmanship increased and the industrial revolution came, standardization of parts led to the shift to mass production. Parts were able to be produced efficiently and repeatedly in order to produce multiple products. For example, during this paradigm, it was easier for Ford to build the same car over and over again, with no differences between them [57]. Yet as knowledge advanced, the manufacturing paradigm shifted to flexible production, where the products could now be customized and vary from each other through flexible systems while maintaining low price points. Finally, high mix, low volume manufacturing was achieved where products being manufactured can vary in application, lot size and production processes within one facility, and where the facility can adjust quickly to a change in product requirements.

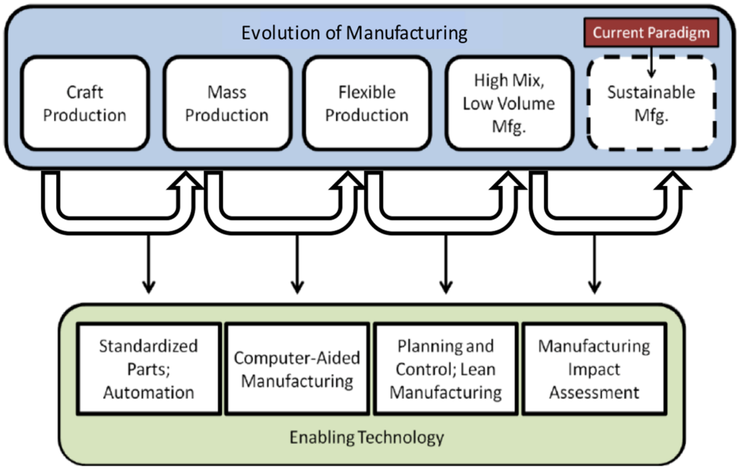

Figure 3. 1 Evolution of manufacturing and the major enabling technology for each shift, adapted from Helu [26]

Yet the benefits of the advanced manufacturing process and equipment technologies have also contributed to resource scarcity and an increase in energy consumption. According to the US Energy Information Administration (EIA), 30% of the nation’s energy consumption was consumed by manufacturers. This is known in the systems literature as the tragedy of the commons [58]; as individuals reap the benefits of a given resource, the demand for the resource will overwhelm the supply causing any additional consumption to harm society. Society has come to realize the importance of this issue and is shifting to the current paradigm, sustainable manufacturing.

Sustainable Manufacturing

“Sustainable manufacturing is defined [by the Department of Commerce] as the creation of manufacturing products that use materials and processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound” [25], [59].

Sustainable manufacturing has concentrated on strategies such as eliminating waste and using recycled materials, integrating renewable energy and reducing emissions, efficient transportation, preventing the use of toxic substances, educating society on the importance of sustainability and redesigning business in order to integrate sustainable development solutions [25].

Moreover, sustainable manufacturing has also led to the development of decision-making tools, metrics, and sustainability measurement systems [60]. Such models concentrate on avoiding short-term economic decisions for long term opportunities due to integration of sustainability; evaluating the relationship between technology, energy, material and pollution; and economic input and output life cycle assessments [60]. Metrics to evaluate sustainability of manufacturing include environmental metrics such as emissions, waste, global warming potential; social metrics such as labor development and welfare, equity, customer satisfaction; and economic metrics such as net present value, life cycle costing, and process time [60].

Finally, the role of technology on sustainability has also gained more attention. Such research has concentrated on the IPAT ($I= P*A*T$) equation, which measures the environmental impacts as a function of population, affluence and technology [25]. Population (P) is as described, the size of the human population under study. Affluence (A) is defined as GDP/capita or as the level of consumption by a certain population. Technology (T) is an impact unit per GDP of a manufactured product and refers to the processes used to obtain and transform resources into goods. Finally, these factors determine the environmental impact (I) or degradation. Environmental impact is expressed in terms of resource depletion or waste accumulation [61]. Looking at this equation, population cannot be controlled, and as the population increases, so does their consumption (A). Therefore, improving the technology (T) factor in the IPAT equation would have the largest impact on the environment. One such technology improvement is additive manufacturing.

3.2 Additive Manufacturing

Additive manufacturing (AM, also known as 3D printing[3]) is the process of creating 3D objects by joining materials layer upon layer [62]. The process melts thin layers of either powder or a spool fed wire of material one layer at a time. It differs from the traditional manufacturing technologies that are considered subtractive processes, such as milling and drilling that cut material away from a block of material.

Additive manufacturing has many advantages over subtractive manufacturing. Parts with complex geometries can be produced without difficulty. Unlike subtractive manufacturing, AM does not require any special tooling and fixtures therefore eliminating constraints and providing geometrical freedom, more precise parts, and complete interlocked parts with no assembly. Other advantages include mass customization of parts due to its geometrical freedom; shorter production time since parts can be printed as ordered with minimal lead time in any location decreasing the need for shipping and storage; and reduced material waste, energy consumption and cost in comparison to subtractive manufacturing processes.

These advantages have allowed AM to enter a new market opportunity for rapid prototyping and manufacturing for design. Manufacturing for design differs from the traditional design for manufacturing in that now instead of *designing products in such a way that makes them easy to manufacture*, products have freedom from design constraints and can be manufactured as pleased. This has allowed AM to enter multiple industries such as aerospace, medical, automotive, construction and art [60].

The flexibility and the introduction of AM into different industries have resulted in its tremendous growth. According to Wohlers Associates Inc., the 3D printing industry grew by $1 billion from 2015 to 2016 to a total of $5.165 billion [63], [64]. In 2015, the industry grew 25.9% from 2014. Over the past 27 years, the additive manufacturing industry has grown at a rate of 26.2%, and in the past three years has grown at a rate of 33.8%. In 2014, the 3D printing industry had its highest growth rate in 17 years equal to 34.9%. The Wohlers Report is based on data collected from 51 industrial system manufacturers, 98 service providers, 15 third-party material producers, various low-cost 3D desktop printers, and 80 3D printing experts from 33

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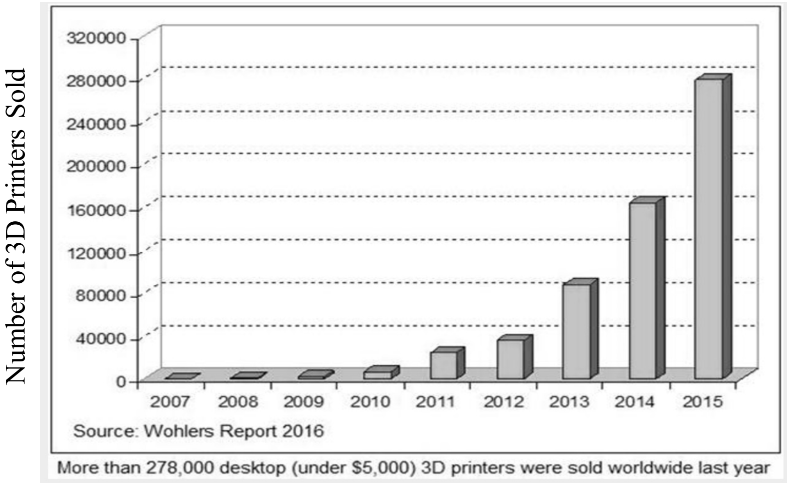
[3] Additive manufacturing and 3D printing will be used interchangeably.

countries [63]. According to Wohlers, in 2015 there were 62 manufacturers of industrial grade AM systems in comparison to 49 in 2014 and 31 in 2011. Desktop AM printer sales increased from 35,508 units in 2012, to 160,000 in 2014 and 278,000 units in 2015.



Source: Wohlers Report 2016

More than 278,000 desktop (under $5,000) 3D printers were sold worldwide last year

Figure 3. 2 Number of printers sold since 2007 by Wohler's Report, adapted from [64]

Industrial AM systems cost over $5000/unit and are distinguishable from lower-end desktop models because they provide higher dimensional accuracy prints for tighter tolerances, high throughput and repeatability of prints, use of a wide range of materials, and can be upgraded for long term use [63], [65], [66]. Moreover, they are typically larger systems that cannot be used in an office, but rather would run from a specific location with the proper HVAC and power systems and expert personnel to print products. Desktop printers cost less than $5000/unit and are typically smaller, thus only capable of printing smaller parts, are material specific, and can be used by individuals at home or in an office environment.

Process

AM typically uses a computer modeling software (Computer Aided Design or CAD) in order to produce the desired sketch of the object [67], [68]. Once completed, the data from the CAD file is read by the AM equipment in 2D to fabricate the object and calculates its mechanical path for printing. Once the path is established, the printer starts to deposit molten or liquid material or solidifies and binds a powder in the 2D shape of the instructions it is receiving from the design CAD file [67]. As the first layer dries, a second layer is then deposited on the first with the same technique. When the second layer dries, a third is added, and this process repeats systematically until the object is printed completely, eventually forming a 3D object.

Technologies

Additive manufacturing technologies can be classified according to the way they print, either by depositing layers of material or binding materials to produce an object. Printers that deposit materials are identified as selective deposition printers. Such a printer *"squirts, sprays, or squeezes liquid, paste, or powdered raw materials through some kind syringe or nozzle* [67]." Printers that bind material do so by using a heat or laser to solidify light sensitive materials (known as photopolymers), or by using an adhesive (known as a binding agent) on a material. These types of printers are called selective binding printers [67]. Printers with lasers and high heat emissions such as the selective binding printers are generally considered to be industrial grade AM and are used in commercial settings. Selective deposition printers are not as dangerous, thus are used in homes and offices.

All printers consist of a printer head. The head is either made up of a lens and a set of mirrors to focus a laser on powdered material, an inkjet for depositing binding agents on powdered material, or a nozzle to squeeze filament material onto a surface.

Selective Deposition Printers

Below are the most common selective deposition printers and a description of how they work.

Fused Deposition Modeling (FDM)- FDM works by taking a plastic filament or a metal wire wound into a coil and feeding it to the printer head [67]–[69]. The material is heated to its melting point then extruded from the printer nozzle onto the base of the printer. The printer nozzle moves according to the path it is given from the CAD file in order to match the design. Once the first layer is deposited, the printer head will slightly rise and deposit the second layer of the design. The second layer binds to the first then cools down and hardens. This process repeats until the object is completed. FDM printers are typically smaller in size and are used in an open space. Yet safety considerations should be taken into account while heating the filament materials. Often the compositions and additives within a material are unknown, and upon heating, fumes are released with unknown hazards.

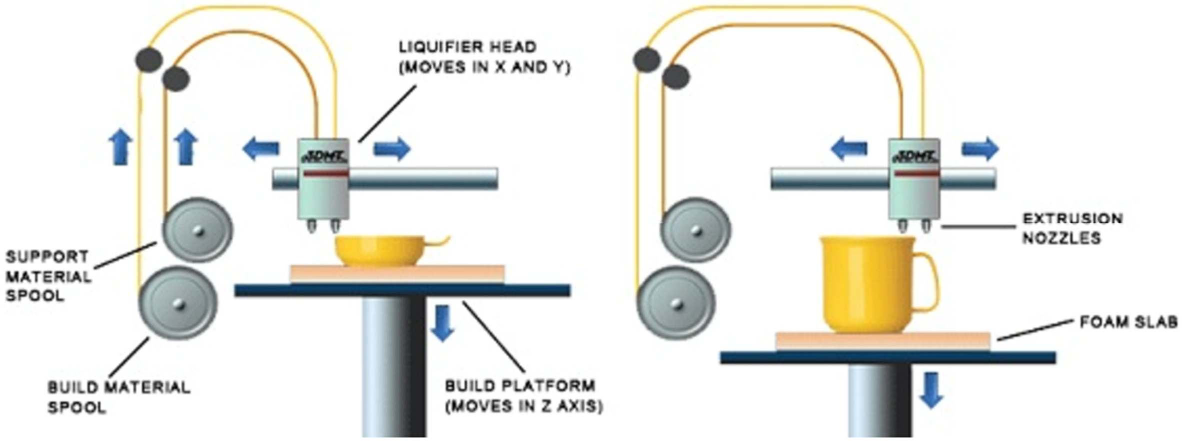


Figure 3. 3 FDM process schematic, from[70]

Laser Engineered Net Shaping (LENS)- LENS is considered to be the most advanced AM process and is best known for its ability to print a wide range of metal and metal alloys for large industrial objects such as in the turbine, defense, aerospace and automotive industries [67], [68], [71]. It works by focusing a high-power laser onto a substrate to melt metal powder that is being supplied coaxially to the focal point of the laser. The metal powder in this process is only applied to where material is needed to create the part at that moment and is distributed either by gravity or using a pressurized gas. The laser hitting the powder creates a molten pool that increases the volume of the object and then cools down. The X-Y table on which the object is being created moves according to the CAD instructions to match the design. After the first layer is complete, the printer head will slightly move upward in order to deposit the second layer. This process repeats until the object is complete. LENS is operated in a closed chamber that is filled with an inert gas such as Argon to keep oxygen levels low in order to print with reactive metals [72], [73].

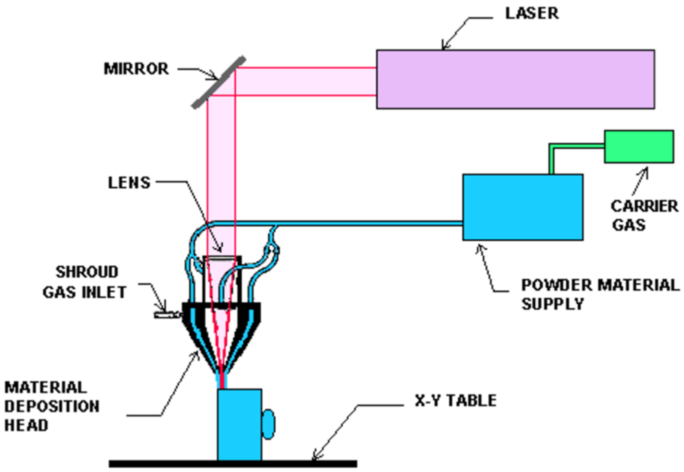


Figure 3. 4 Laser engineered net shaping process schematic, from Xiong et al. [74]

Laminated object manufacturing (LOM)- LOM laminates or fuses together layers of adhesive coated paper, plastic or metal sheets using heat and pressure in order to create an object [67], [75], [76]. It works by rolling a sheet of material onto a platform and using a computer controlled laser or knife, the desired shape is cut out from the sheet. The cut-out shape is then left on the platform and the platform is lowered in order to roll a new sheet of material and cut out the second layer. Once the second layer is on the platform along with the first, a heated roller moves over the top to bond the layers together. This process is repeated, with each additional cut out layer adhered to the rest of the object using the heated rollers. LOM printers are operated in an open space and can print relatively larger objects than the rest of the technologies. Moreover, the materials typically used are available and well understood [76]. The environmental hazards that may result from LOM are due to the toxicity of the binding resin used.

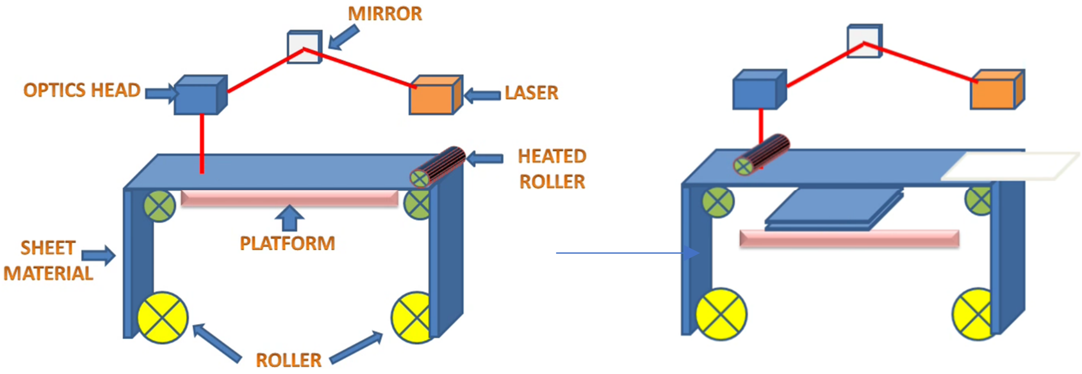


Figure 3. 5 Laminated object manufacturing process schematic, from [75]

Polyjet Printing- Polyjet printing involves spraying (or jetting) photopolymer liquid materials from multiple print heads onto a build platform in layers as thin as 16 microns [67], [77]. Each layer is simultaneously cured by a UV light, therefore solidifying the layer. The platform is lowered as each layer is printed in order to print the next within the printer. The advantage of polyjet is that a user can print with multiple materials and colors in one print, due to the multiple spray heads. Moreover, this type of printer is also considered to be the most economical printer and can print high resolution parts with complex geometries, accurate detail, and smooth surface finish and it prints parts fast. Polyjet printers are enclosed due to the jetting of the toxic photopolymer liquid.

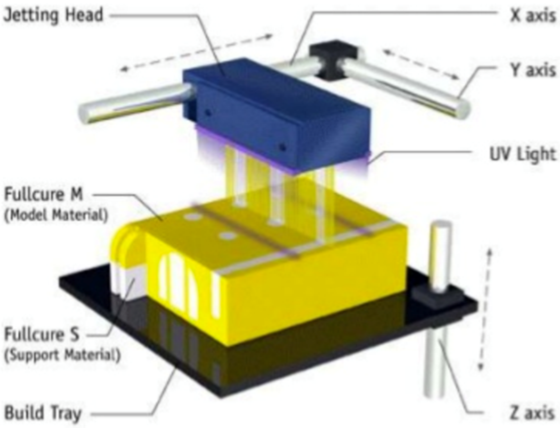


Figure 3. 6 Polyjet process schematic, from [78]

Selective Binding Printers

Below are the most common selective binding printers and a description of how they work.

Stereolithography (SLA)- SLA is the one of the earliest commercial printers. It is made up of a vat (a large tank) holding a photopolymer liquid, a moving platform and a UV laser [67], [70], [79]. The platform starts immersed one layer beneath the photopolymer and a UV laser is traced onto the surface of the liquid thus curing and hardening the liquid into a solid in the shape of the traced pattern. The platform is then slightly lowered to obtain a new layer of photopolymer resin and the process is repeated. Each added layer joins the layer below and the printed object sinks into the liquid as it is being printed. Some SLA printers aim the laser upwards in order to work in the opposite direction and lift the printed object instead. After the object has finished printing, it is rinsed off to get cleaned and sometimes needs additional sanding and smoothing. SLA printing is fast and precise, and although the printers are enclosed in a chamber, toxic fumes are present during the printing and post-processing process from uncured photopolymers.

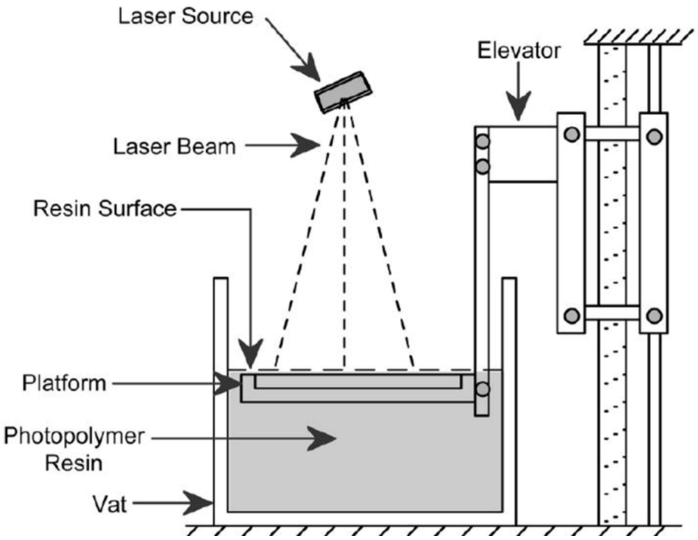


Figure 3. 7 Stereolithography process schematic, from Atwell [80]

Digital Light Projection (DLP)- DLP is a type of SLA but works with conventional sources of lights like arc lamps instead of lasers [81]. It has the same environmental implications as the SLA due to the toxicity of the resins used.

Selective Laser Sintering (SLS)- SLS is similar to SLA except that it uses powdered material without polymer binders instead of liquid materials. A layer of material powder is brushed onto a platform using a roller and a high-powered laser beam traces over the powder in order to melt and bind it into the desired shape [67], [70] . The platform is then slightly lowered and a new layer of powder is brushed and the process repeats until the object has finished printing. The powder acts as a support structure to the printed object, but when the print is complete, the object must be dug out of the powder. SLS prints are done in a sealed chamber filled with nitrogen in order to avoid explosions from mishandled powders.

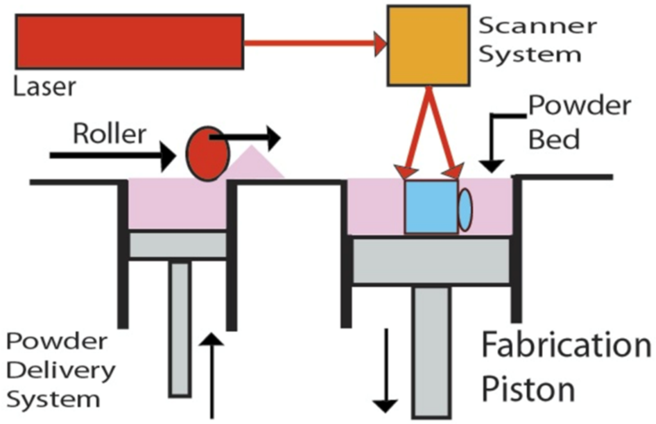


Figure 3. 8 Selective laser sintering process schematic, from [70]

Selective Laser Melting (SLM)- SLM is similar to SLS but actually melts the powder instead of sintering it [81]. The environmental concerns of SLM are the same as those of SLS, the powders may be toxic and explosive. Moreover, melting the powders may release hazardous off-gasses.

Three-Dimensional Printing (3DP)- 3DP is very similar to SLS, but instead of using a laser beam, it deposits a liquid adhesive onto raw powdered material in order bind them together to form the desired object. The platform is then slightly lowered and a new layer of powdered material is brushed onto the surface. This process repeats until the object is printed. 3DP are energy efficient due to the lack of laser, can print in color by adding droplets of colored ink into the adhesive, and can be used with a wide variety of powders, yet objects printed here tend to have rough surfaces [67].

Table 3.1 highlights the printers discussed above and their classification according to the way they print; either by depositing materials or binding materials. The hazards associated with the printers are process dependent. Hazards are caused by either the toxic binders or resins being used, reactive powders, or from heating and melting materials.

Table 3. 1 Classification of 3D printing technologies

Selective Deposition Printers	Selective Binding Printers
Fused deposition modeling Laser engineered net shaping Laminated object manufacturing Polyjet printing	Stereolithography Digital light projection Selective laser sintering Selective laser melting Three-dimensional printing

Materials used in 3D Printers

Initially, additive manufacturing technologies had a limited database of materials that could be used. Each printer was optimized to print specific materials and due to the high purchasing cost of the printers, material testing was discouraged in order to not damage them. As the technology advanced, material manufacturers were encouraged to develop higher performance material. Currently, materials used in AM include plastics, polymers, metals, composites, ceramics and other advanced and new materials such as biological material. These materials most commonly come in the form of powder, filament, pellets, and liquid resin.

Plastics and Polymers

Plastics are the most commonly used materials in 3D printing [67]. Plastics fall under two categories: thermoplastics polymers and thermosetting polymers [67]. Thermoplastics are those plastics that can be melted and re-melted multiple times without changing their internal composition, and are mostly used in FDM printers. Thermosetting polymers solidify when heated thus changing their internal composition and cannot be re-melted in order to be used again. Such plastics are usually used in SLA printers.

Some frequently used plastics in AM are [67], [68], [82]

- Acrylonitrile butadiene styrene (ABS)
- Polylactic acid (PLA)
- Polyvinyl alcohol (PVA)
- Polycarbonate (PC)
- High impact polystyrene (HIPS)
- Nylon

The advantages of using plastic materials include design flexibility and durability, biodegradability for some bioplastics, and their availability in multiple colors. However, plastic materials are likely to warp with heat.

Metals

Metals tend to be strong, malleable and ductile in comparison to plastics, yet have low design flexibility and are costly. Most metals in AM come in powder form although more recently some metals have been mixed with PLA in order to be shaped into filaments for FDM printers.

Some frequently used metals in AM are [83], [84]

- Stainless steel
- Steel
- Titanium
- Gold
- Silver

Specialty and Other Materials

More research is being conducted on specialty materials that can be used in additive manufacturing. Bio-materials are growing for medical applications whereas composites are interesting due to their higher performance mechanical properties [67].

Some frequently used specialty materials in AM are [67], [83]

- Composites
- Ceramics
- Rubber
- Bio-ink
- Glass

Figure 3.9 summarizes the types of materials used in 3D printing, their associated material state– solid, liquid or powdered, and the types of printers those materials are generally associated with. Unlike Table 3.1, the printers are not divided into the two categories of depositing materials or binding materials, rather Figure 3.9 provides a more descriptive overview of the processes each material state undergoes in each printer. The next section addresses the potential environmental impacts of these materials.

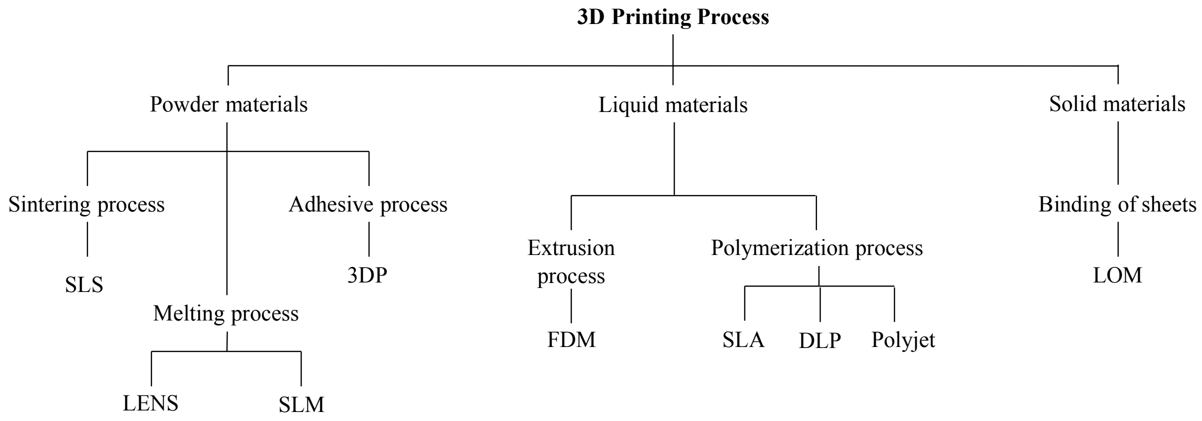


Figure 3. 9 3D printing process technologies and materials, adapted from Srivatsan and Sudarshan [83]

Sustainability Implications of 3D Printer Technologies

With the growth of 3D printer technologies, emphasis on their environmental and social impacts has increased as well. More specifically, literature has emphasized the positive aspects of 3D printing such as customized healthcare and products to increase the quality of life, reduced manufacturing impacts, simplified supply chains and increased efficiencies [62]. Yet, there has been less research on hazard assessments for potential occupational risk as well as a life cycle assessment for AM. It is important to note that there are two types of hazards related to 3D printing; handling hazards and exposure hazards. Handling hazards refer to the physical hazards associated with using or storing a material. For example, during FDM printing, the material exiting the extruder will be too hot to touch and may cause burns if a person is in contact with it. Exposure hazards relate to breathing, inhaling, or being in contact with various toxic substances or chemicals that may cause short term or long term illnesses.

The states in which 3D printing materials are made (Figure 3.9) have different material health implications:

> ***Solid materials*** generally have fewer handling hazards, yet exposing them to high temperature conditions may result in exposure hazards from material degradation [85], [86].
>
> The chemical composition of ***liquid materials*** such as the liquid photopolymer resins used in SLA is usually not disclosed by the manufacture [87], yet it is common knowledge that photopolymer resins contain hazardous and toxic monomers and can create toxic fumes while printing. Moreover, after printing, the product must be washed in solvents in order to remove the remaining uncured liquid. The washing solvent may also be corrosive and would then contain hazardous monomers in it after the wash [86].
>
> ***Powdered material*** can be inhaled easily and distributed in the work space. Depending on the material, it may be toxic, hazardous or an irritant to the lungs, eyes, and skin. It may also be flammable [86], [88].

Thus, it is important to understand the human health and environmental hazards[4] associated with different materials printed. The 3D printer and material hazards presented in this chapter are generic and not applicable to all materials. Material hazard research must focus on each specific material and the printer it is being used in. This complication will arise again in Chapter 5 where development of the model is described.

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[4] For this dissertation, the use of the terminology of "hazards" will specifically refer to exposure hazards and not handling hazards. Moreover, the use of the terminology for "material hazards" is interchangeable with "material sustainability."

Chapter 4

Additive Manufacturing Standards, Regulations and Material Selection Tools

The user interviews conducted in Chapter 2 highlighted that material sustainability is limited to meeting government regulations. This chapter outlines the standards and regulations applicable in the additive manufacturing industry, along with the current methodologies and tools used to evaluate material sustainability in any industry, in order to understand how sustainable material decisions are currently influenced. This chapter ends with a series of interviews conducted with people in the additive manufacturing industry to understand material selection within the additive manufacturing industry.

4.1 Standards and Regulations

Even with all the possible hazards associated with 3D printing technologies and materials, currently, the additive manufacturing (AM) industry lacks specific AM standards and regulations [89]. According to the International Organization for Standardization (ISO), a **standard** is a "document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose [90]." ISO in an independent, non-governmental international organization founded in 1947 that brings together experts to develop these voluntary standards to support innovation. On the other hand, a **regulation** is a government imposed requirement on a specific product, process or service that has mandatory compliance [91], [92].

Standards

Over the course of AM growth, standards of other industries, products, processes and materials have been applied to the products produced by AM. Yet, experts have agreed that the largest barrier to broad AM adoption is the lack of specific standards and that existing standards are not suitable or specific enough for AM [89]. Several factors related to the printing process such as print direction affect the end result of the printed product. Thus, two manufacturers that use the same material and printer could print a product with different characteristics. Therefore, a lack of standards hinders the qualification and certification of a printed part to enter specific industries such as medical, aeronautical or automotive[5], where certification is mandatory. Other barriers of adoption include understanding how the printer, printing parameters, and printing process affect material types and properties, performance, part accuracy, surface finish, fabrication speed, and build volumes/part size [89]. Thus, ISO and the American Society for Testing and Materials (ASTM), along with the support of other technical groups and projects have focused their efforts to provide new standards for AM.

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[5] Some exceptions apply. There has been 3D printed parts that have entered these spaces, yet generally, their acceptance is hindered due to qualification issues.

Highlighting the lack of standards in industry and addressing the relationship gaps between the printer, printing parameters and process, and materials provides an understanding of the role that standards can play in the AM industry. Although standards will help address the connection between materials and part quality and help designers and engineers select the right material for their product, the standards do not address material sustainability.

American Society for Testing and Materials

ASTM created the ASTM International Technical Committee F42 on Additive Manufacturing Technologies in 2009. It consist of over 550 members from 26 countries that meet twice a year [93] with the "objective of the promotion of knowledge, stimulation of research, and implementation of technology through the development of standards for AM technologies [94]." The F42 is comprised of the following seven technical subcommittees [93]:

- F42.01 Test Methods
- F42.04 Design
- F42.05 Materials and Processes
- F42.06 Environmental, Health, and Safety
- F42.90 Executive
- F42.91 Terminology
- F42.95 US TAG to ISO TC 261

So far, 15 standards have been approved and more are under development [89], [93]. Of the ones approved, standard F2792-12a, Standard Terminology for AM has been of interest to the AM community. There has been a large debate on the nomenclature commonly used, beginning with the definition of AM, the inclusion of rapid prototyping and rapid manufacturing, and on the classification of AM technologies. So far, F42 has categorized AM processes into seven areas [89]:

1. Vat photopolymerization (e.g., stereolithography, SLA)
2. Material jetting (e.g., Polyjet)
3. Binder jetting (e.g., 3D printers using powder and binder)
4. Material extrusion (e.g., FDM)
5. Powder bed fusion (e.g., SLS)
6. Sheet lamination (e.g., Sheet Forming)
7. Directed energy deposition (e.g., laser cladding)

The AM categories listed above aim to classify the printers according to the process they undergo. Figure 4.1 below aims to match the 3D printers described in Chapter 3 to the ASTM terminology.

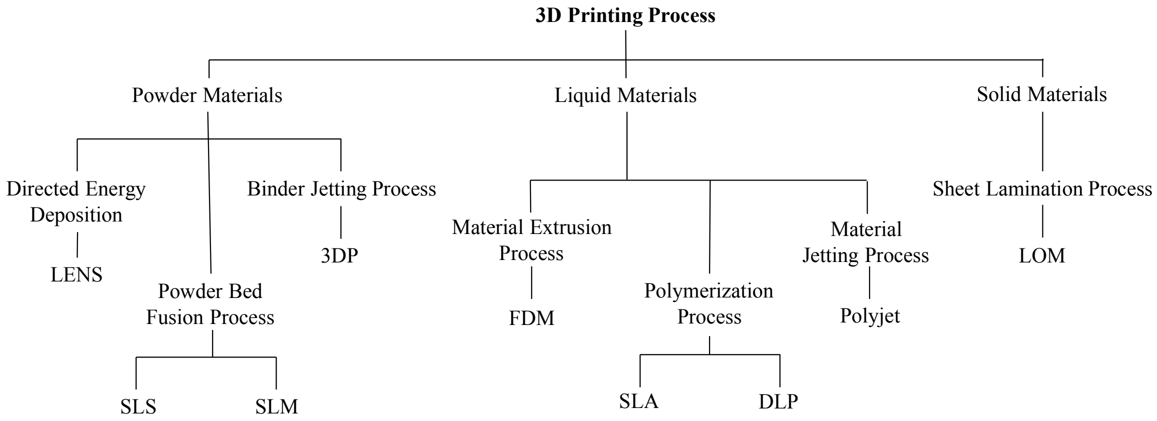

Figure 4. 1 Classification of 3D printing technologies and materials according to ASTM terminology, adapted from Srivatsan and Sudarshan [83]

International Organization for Standardization

In 2011, ISO created the Committee TC 261 on Additive Manufacturing Technologies (ISO TC261). It is composed of 22 participating countries and six observing countries. The objective of ISO TC 261 is to provide "standardization in the field of Additive Manufacturing concerning their processes, terms and definitions, process chains (hardware and software), test procedures, quality parameters, supply agreements, and all kind of fundamentals [95]." So far, they have published six ISO standards and have seven under development. ISO TC261 is comprised of the following four technical subcommittees [89]:

- ISCO/TC 261/WG1 Terminology
- ISCO/TC 261/WG2 Methods, Processes, and Materials
- ISCO/TC 261/WG3 Test Methods
- ISCO/TC 261/WG4 Data Processing

Within the four technical subcommittees of ISO TC261, each works in two fields: The first is to develop original standards for AM and the second is to study other standards developed by external bodies such as ASTM and to adopt those standards of interest.

ASTM-ISO

Although ISO and ASTM have been working independently on their AM standards, in July 2013 during a meeting held in Nottingham, UK, ISO TC261 and ASTM F42 agreed to develop joint standards. The aims of this collaboration are to [89][96]:

- Create one set of AM standards to be used worldwide to guide the work of experts and improve usability
- Develop a common AM standards road map and organizational structure
- Use and build upon existing standards to be modified for AM when necessary in order to fill in data gaps
- Work together and in the same direction to develop joint standards for efficiency, effectiveness, and cohesion

The preliminary working groups are composed of

- Design guidelines
- Standards test artifact
- Requirements for purchased AM parts
- Harmonization of existing ISO/ASTM terminology standards
- Standard specification for material extrusion based additive manufacturing of plastics

Figure 4.2 highlights the joint consensus of ISO TC 261 and ASTM F42 with regards to the structure for developing AM standards. Its aim is to facilitate the development of standards, reduce the risk of duplication and reduce the risk of contradiction between standards. It is divided into three levels [89], [96]

- General AM Standards: General concepts, common requirements, guides and safety
- Category AM Standards: Specific to materials or process category
- Specialized AM standards: Specific to a material, process or application

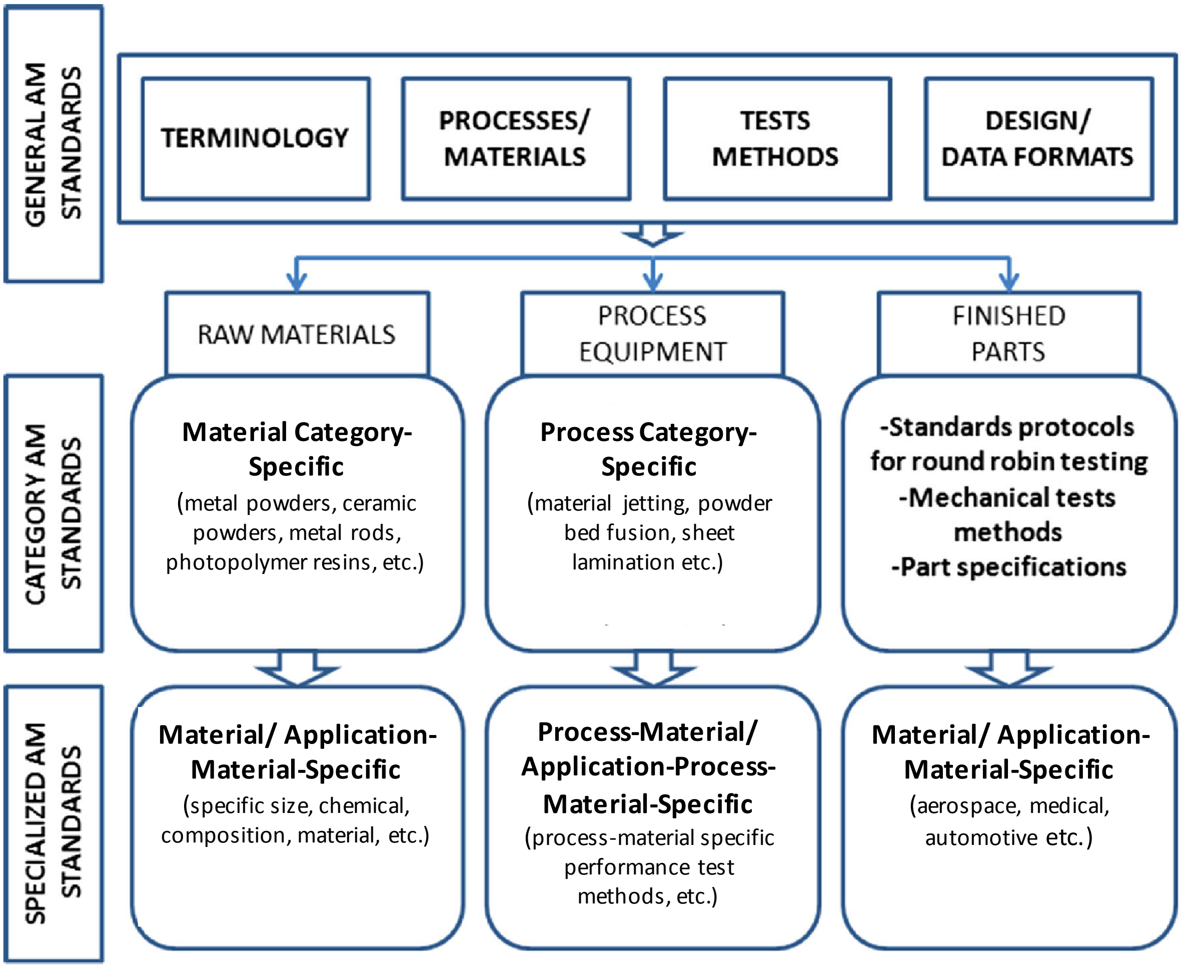

Figure 4. 2 ASTM-ISO additive manufacturing standards structure, adapted from Monzon et al. [89]

Other organizations such AFNOR (France), ENOR (Spain), VDI/DIN (Germany), and CEN/TC 438 (European Standards Technical Committee) have contributed to national standards, but the ASTM and ISO standards-making bodies are the largest contributors to date [89].

Developing standards specific to the AM industry will set the context for materials choice decisions. The more detailed they are with regards to materials, process and finished parts, the more likely they will influence materials decisions and make the material selection process easier, specifically for products being printed for industries that have qualification requirements. Yet, although the standards under development aim to test process specific performance, they will not likely include the trade-offs between materials, material costs, and sustainability. This would make it difficult for a designer or engineer to select materials based off these standards alone. A platform that combines what engineers frequently cited as important; performance, costs, aesthetics, along with industry standards and material will facilitate material decision making during the product design and development process.

Regulations

Regulations are set by governing bodies and require mandatory compliance. There are no specific additive manufacturing regulations, yet certain products produced by AM must comply with the regulations relevant to its application. Below is a list of the most common regulations that are followed by the AM industry.

Restriction of Hazardous Substances (RoHS)

This is a mandatory worldwide regulation that originated in the European Union. It bans the use of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls, polybrominated diphenyl ethers, and four different phthalates (DEHP, BBP, DBP, DIBP) due to their hazardous impacts to the environment and landfills, as well as occupational health hazards resulting from exposure during manufacturing and recycling. For electrical and electronic equipment that require the use of these materials, RoHS dictates the maximum levels of use [97]–[99]. Materials being developed for AM may not therefore contain these substances listed. Moreover, as AM develops to produce whole electronic products or housings such as laptops and televisions, these too will have to meet RoHS standards in order to certify the products are safe for users.

Waste from Electronic Equipment (WEE)

This EU directive "mandates the treatment, recovery, and recycling of electrical and electronic equipment [98]" in order to manage the environmental and human health impacts related to these products [99], [100]. Therefore, when a product is being produced by 3D printing, the materials used must meet these waste regulations and provide a means of environmentally safe recovery and recycling.

Registration, Evaluation, Authorization, Restriction of Chemicals (REACH)

Is an EU regulation that addresses the production and use of chemical substances, and is "…adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals, while enhancing the competitiveness of the EU chemicals industry. It also promotes alternative methods for hazard assessment of substances in order to reduce the number of tests on animals [45]." REACH applies to all chemical substances found in our day-to-day lives and in industrial processes, and "…places the burden of proof on companies. To comply, companies must identify and manage the risks linked to the substances they manufacture and market in the EU. They [also] have to demonstrate to ECHA how the substance can be safely used, and they must communicate the risk management measures to the users. If the risks cannot be managed, authorities can restrict the use of substances in different ways [45]". REACH may have the largest implications on the AM industry. Any product printed in the EU or printed abroad and sent to the EU will have to meet the REACH regulations. This therefore implies, any printed product that will come into interactions with a user, such as toys must be tested for hazard exposures and the chemicals contained in their product. Hazard exposures and chemicals are embedded into the material decisions that are made prior to printing.

U.S. Food and Drug Administration (FDA)

The FDA's regulatory scope is very broad. It is responsible for "assuring the safety, effectiveness, quality and security [101]" of multiple categories of products including human and veterinary drugs, biological products, medical devices, food, cosmetics, tobacco products, and electronic products that give off radiation. Each category has a list of regulations that must be followed if the product being produced falls under its scope [102]. FDA regulations also have a large impact on the AM industry. One of the hypes about AM is its ability to print prosthetic limbs and medical devices, yet any of these products will have strict regulations under the FDA. In addition, simple products such as food containers, that are often printed in the AM industry, must meet FDA regulations too before going to market. These regulations often address the types of materials being used, their hazards, and other specific requirements depending on the application.

California's Proposition 65

The Office of Environmental Health Hazard Assessment (OEHHA) administers Proposition 65 which "requires the State to publish a list of chemicals known to cause cancer or birth defects or other reproductive harm [and] …requires businesses to notify Californians about significant amounts of chemicals in the products they purchase, in their homes or workplace, or that are released to the environment. [The intention of this Proposition is] …to enable Californians to make informed decisions about protecting themselves from exposures to these chemicals. Prop 65 also prohibits California business form knowingly discharging significant amounts of listed chemicals into sources of drinking water [103]." Prop 65 was first published in 1987 and is updated at least once a year [46]. Therefore, any printed products that contain any of the chemicals and materials listed under Prop 65 will have to declare they may be harmful to their users.

Other

Other non-governmental regulations may be set as internal regulations within a company that must be met according to their company values. Companies interviewed for this research, for example, mentioned UL (Underwriters Laboratory) certifications. The list above includes just regulations that are legally binding; there are many opportunities for companies to obtain certifications that are not included.

The regulations highlighted above display the complexity of following them depending on both the region and industry a manufacturer is part of. In addition, interpreting these regulations to adopt them with AM materials complicates the process further. Due to the number of standards and regulations that manufacturers need to be aware of when evaluating materials, it highlights why industries tend to stick to grandfathered materials as an "accepted materials" list instead of evaluating and using new materials.

Material Performance in Additive Manufacturing

The lack of standards and regulations specific to AM have created barriers to adoption in the AM industry. Moreover, material-specific standards do not yet exist and have been demanded for AM processes. Creation of such standards is complicated by the growing number of new materials that are being developed, and by the fact that AM materials behave differently under different printing conditions.

With the growth in AM, an interest in development of new AM materials has also grown. Initially, existing materials dictated AM technologies, however these materials were not always the best suited. For example, earlier prints made from photocurable resins were brittle and warped easily and lasers that melted powders resulted in weak parts [68]. As AM processes advanced and the technology was understood better, new materials were developed to match the operating parameters and processes that withstood higher temperatures and were more suitable for smaller features and faster throughput. These new materials resulted in better printed products. Such materials include polymers that consist of a wide range of properties and applications (e.g., glass filled polyamides, polyamide based powders, amorphous polymer materials, elastomeric thermoplastic polymers), biocompatible materials developed for specific medical applications and proprietary metal powders (e.g., powders that contain copper, stainless steel bronze) and ceramics.

Multiple studies have reported a difference in a given material's mechanical properties depending upon print direction, process parameters such as thickness and speed, and even the amount of recycled powder in some cases [104]–[108]. Studies have variously found through tests on metals and plastics with AM technologies that the following factors affect the performance of those materials [89]:

- General properties such as density, moisture absorption
- Mechanical properties such as tensile strength, tensile modulus, izod impact
- Thermal properties such as heat deflection temperature, specific heat capacity
- Electrical properties such as volume resistivity, surface resistivity

To date these tests do not address the specific environmental hazards associated with the materials.

4.2 Safer Material Selection Methods and Tools

Existing material databases, frameworks and tools, not specific to AM, aim to help identify the negative environmental and human health impacts associated materials in industry and help select safer materials. Data sources identify chemicals that are hazardous or potentially hazardous, frameworks provide guidance to conduct hazard, risk, alternative, or life cycle assessments, and tools provide the means to perform the assessment using databases as input to the framework methodologies. Figure 4.3 outlines the relationships between databases, frameworks, tools, and assessment methodologies.

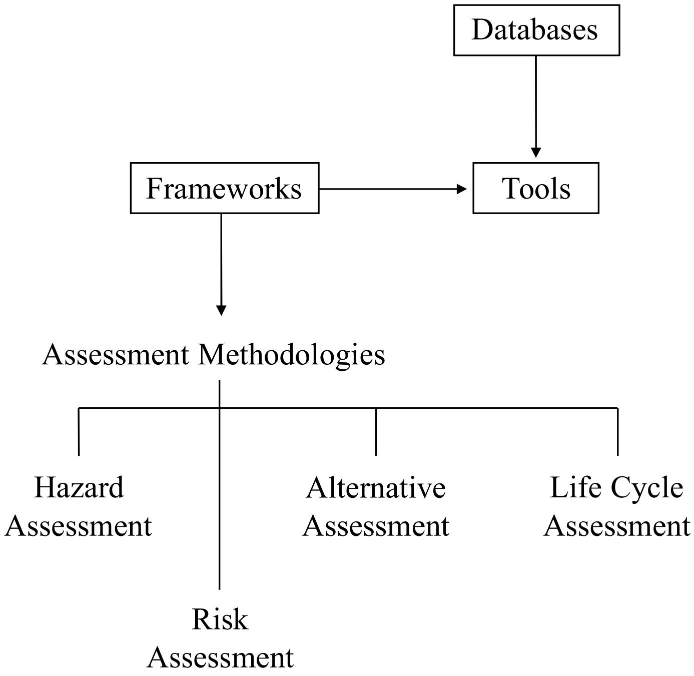

Figure 4. 3 Relationship between databases, frameworks, and tools

Before addressing the available databases, frameworks, and tools, it is important to distinguish between hazards, exposure, and risk. Certain chemicals pose harmful human health and environmental effects known as a chemical hazard. The chemical hazard is the result of the structure of the molecule, thus it is inherent and cannot be changed [109]. Exposure is the state of being in contact with a substance while risk is the likelihood that an adverse effect will occur from exposure [110].

In addition, the frameworks mentioned above guide assessment methodologies. There are four methodologies for conducting sustainable assessments. They include chemical hazard assessments, risk assessments, alternative assessments, and life cycle assessments.

Chemical Hazard Assessment

A chemical hazard assessment is a "method for comparing chemicals based on their inherent hazard properties [111]." Hazard assessments evaluate a range of specific adverse outcomes, known as endpoints, and their level of severity. The level of severity is based on the strength of evidence of a chemical to trigger that endpoint. Endpoints can be broadly categorized into human health, environmental, and physical hazards. Figure 4.3 provides an overview of the 18 most commonly used endpoints for each category. The description of each endpoint can be seen in Appendix A.4.

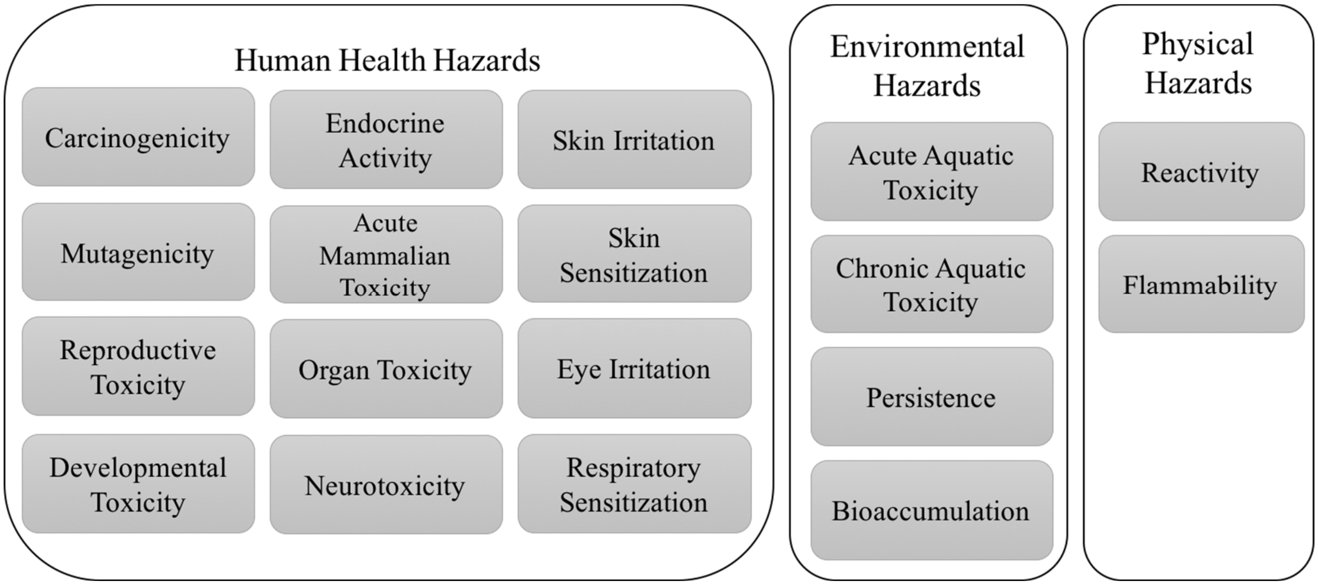

Figure 4. 4 Hazard assessment endpoints

Risk Assessment

In addition to hazards assessments, risk assessments are often conducted. A risk assessment is the likelihood of the chemical hazard to cause harm and the severity of its consequences. Risk is based on estimating the hazard, vulnerability and exposure of a chemical [112]. Vulnerability is associated to the population that will be affected by the hazard whereas exposure studies the route, duration, frequency and intensity of contact.

Well-informed materials choices require understanding hazards as well as the risks they represent. Hazard data is available from a range of government sources yet risks are typically evaluated by the use case scenario.

Alternative Assessments

Alternative assessments aim to identify and compare potential chemical and nonchemical alternatives (such as materials or product designs) that can be used as substitutes to replace hazardous substances, chemicals or technologies of high concern on the basis of their hazards, performance, and economic viability [110], [111]. This assessment methodology places value on avoidance of hazards by substituting the use for safer chemicals or materials instead of using exposure controls as a risk assessment does. Moreover, it addresses whether alternatives are available, perform adequately, and are cost effective [110]. Multiple alternative assessment frameworks exist, and will be discussed below.

Life Cycle Assessment

A life cycle assessment (LCA) is a “systemic evaluation of environmental impacts from the provision of a product or service [113].” The principles and framework for LCA framework developed by the International Organization for Standardization (ISO 14040:2006). Figure 4.5 highlights the LCA methodology described by ISO.

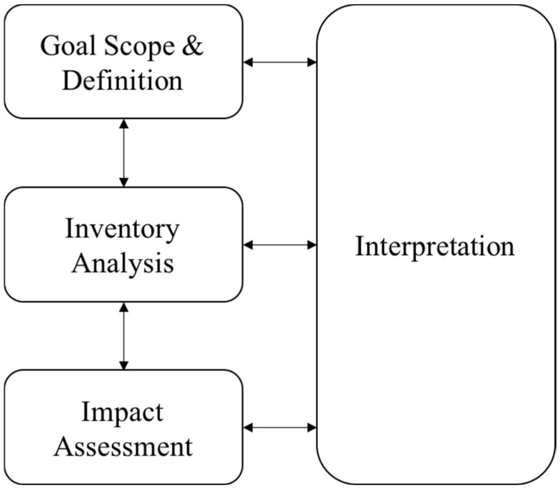

Figure 4. 5 LCA Framework developed by ISO 14040:2006

Defining the goal and scope determines the limits of the LCA analysis. This step includes identifying which stage(s) in the product or service's life cycle to assess (raw material extraction, production, use, and end of life) and a functional base for comparison. The components involved, the inputs to those components, and the outputs, wastes, and emissions from those components at every stage make up the inventory analysis. The inventory data is then fed into an algorithm that determines the effects and impacts of the inventory [113]. For example, the fossil fuel energy used in the inventory input is converted into climate impacts and air pollution [113]. The impact assessment algorithm consists of four steps: classifying substances according to their environmental effect, known as classification; multiply the substances by a factor to reflect their contribution to the impact, known as characterization; normalizing the impacts on a reference value; and finally weighing the impact categories for a final single score [114]. Geographical location, data quality, and technology or process also influence the impact assessment, although not always indicated [114]. In addition, the impact assessment can be conducted on mid-point impact category or end-point impact category. Midpoint impacts are translated into environmental themes, such as climate change or human toxicity whereas endpoint impacts are damage oriented and translate into issues of concern. Endpoint data impacts are easier to understand yet have higher level of uncertainty [114]. Finally, the results are interpreted in order to reduce the impact of the product or service.

The limitations of LCA is that it often concentrates more on environmental impacts than human health impacts. Moreover, LCA does not restrict the use of problematic or toxic chemicals and does not note toxicity; it only evaluates trade-offs among impacts and the impacts that may occur through a product's life cycle.

Figure 4.6 is an overview of assessment methodologies to be discussed in the next section. The classification of these resources is not based on previous work and they are not all mutually exclusive.

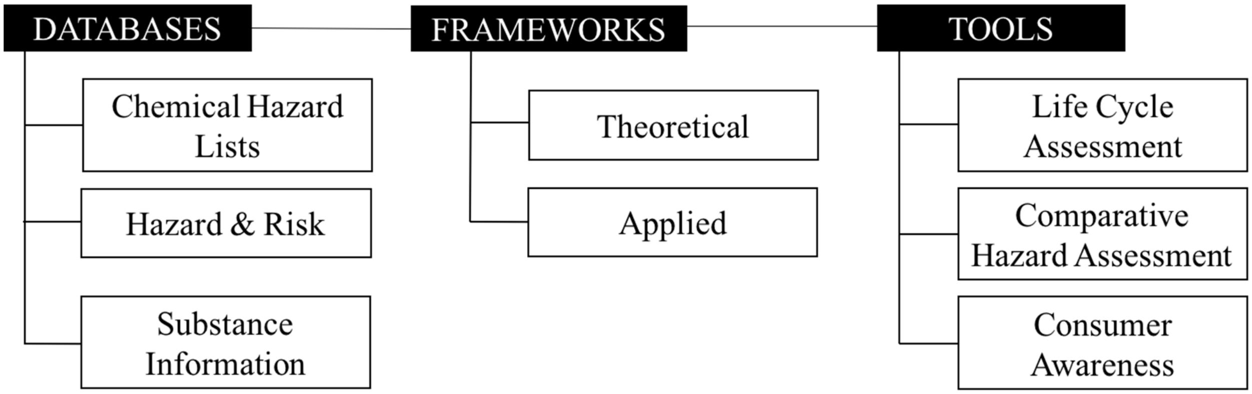

Figure 4. 6 Overview of material assessment methodologies

Material Databases

Material databases are lists or sets of data that provide information on chemicals and identify them as hazardous or potentially hazardous. Generally, databases are composed of chemical hazard lists, hazard and risk lists and substance information lists. These databases can act as a first screening guide to the chemical and materials being used in a product. Chemical hazard lists could be authoritative hazard lists that are maintained and reviewed by governing bodies and scientific councils or non-authoritative lists that are developed by other groups, initiatives or even industries. Examples of authoritative chemical hazards list include CA Proposition 65 and International Agency for Research on Cancer (IARC). As discussed above, Prop 65 [46] lists chemicals and materials known to cause cancer or birth defects or other reproductive harm while IARC [115] studies and reports on chemicals that can cause cancer. Multiple other authoritative chemical hazard lists exist that vary according to the hazard they are addressing or the governing country that is creating the list. Non-authoritative hazards list also aim to identify and restrict the use of chemicals but are may be non-government binding. For example, restricted substance lists (RSL) have been created for the apparel industry by the American and Apparel Footwear Association and others RSLs for industries discussed in Chapter 1.

Hazard and risk databases look at the hazards and associated risks of chemicals and materials, and often include precautionary safety measures to limit exposure. Such databases include Material Data Safety Sheets (MSDS) and the Swedish Chemical Agency database Priority Setting Guide (PRIO) [116]. MSDS now known as safety data sheets (SDS[6]) are widely used to provide information on chemicals and chemicals compounds and mixtures. They are intended to be used by people who are handling a certain chemical in an occupational setting. Historically, multiple MSDS sheets were provided with varying information based on the country of origin's reporting requirements. In 1999, the Global Harmonized System (GHS) of Classification and Chemicals, set out to standardize the reporting requirements on MSDS. The purpose was to provide an international system and framework for reporting comprehensive hazard data in order to enhance the protection of human health and the environment and to facilitate trade. statements The information required to be reported is divided under 16 headings, summarized in Appendix A.4. Prio on the other hand, is a database that contains substances that have environmental and

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[6] The abbreviation MSDS will be used in this work instead of SDS to emphasize material safety.

human health hazards and provides guidance to prevent risk associated with these substances. Although any users can obtain information from Prio, the information it provides is targeted for Swedish actors [116]. For this research, MSDS sheets will be used since the information they provide are globally standardized.

Finally, other initiatives have directed their efforts to compile available data on chemicals and materials into one database and act as general substance information. One such database is The Pharos Project (Pharos). Pharos is a database that was designed to evaluate hazards associated with building products and components for the Healthy Building Network that now incorporates 46,525 chemicals and materials in their database [117]. The hazard information collected is based on 44 authoritative lists of hazards issued by governments, scientific research and expert bodies, and other NGOs and 28 restricted substance lists [117]. The lists used by Pharos can be found in Appendix A.4. Other databases include the Substitute It Now (SIN) List by the International Chemical Secretariat (Chemsec) [118]. It identifies substances with very high hazard concerns based on EU's REACH criteria, and compiles it into one location for users to be able to see if the substances going into their products are safe or not. RISCTOX [119] is another database that contains hazardous substances and provides information on the health and environmental risks caused by each substance, their classification, and advice and links on related regulations.

Is it important to note multiple hazard lists and databases exist. For example, the Pharos database alone contains 77 hazard lists that they use for their database. Also, many of these databases are not mutually exclusive, rather they are used in tools or as tools sometimes, to be discussed below.

The databases that exist aim to help users identify the hazards associated with the chemicals and materials that are going into their products. Yet, there are so many databases, it often is not clear which one to use. Some databases address specific hazards while others address all available hazards related to a substance yet with regulations specific to the country of origin. Moreover, some of the databases do not have information on a substance in order to specify its hazards, yet that does not mean no hazards exist.

Frameworks

Frameworks provide the means to conduct an assessment methodology. The figures that represent each framework discussed below are available online from the sources referenced. They are included here to have a thorough representation of this body of research material in one place.

Although many frameworks exist, there are two primary paradigms for chemical hazard assessment frameworks; US Environmental Protection Agency Design for the Environment Alternative Assessment (EPA DfE) and Clean Production Action's GreenScreen [120]. These two frameworks instruct the user to conduct a literature review to identify the human health and environmental effects, the data gaps of substances, and assess the information to determine if an alternative is less hazardous.

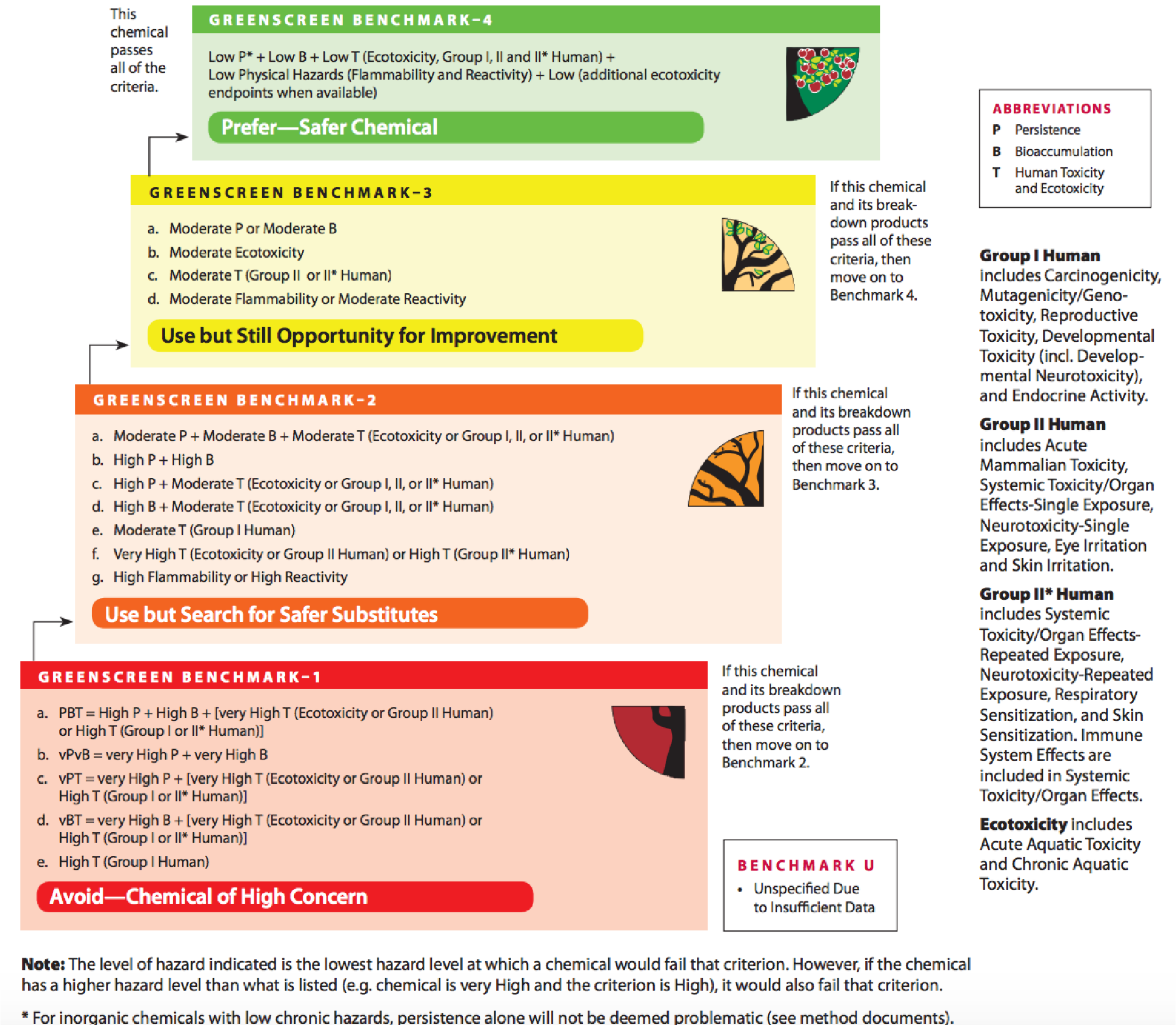
The EPA's DfE [121] estimates the hazards associated with human health and environmental endpoints and categorizes them into very high, high, moderate, low, and very low hazard impacts. Their report indicates data from all exposure types (oral, dermal, or inhalation) must be evaluated, authoritative lists on where to obtain this information must be provided as well as how to interpret the data. The data limits for each hazard category can be seen in Appendix A.4. Based on the hazard assessment, safer substitutes are made. Figure 4.7 shows the US EPA's DfE alternative assessment criteria for hazard evaluation.

Figure 4. 7 US EPA Design for the Environment Alternative Assessment for Hazard Evaluation, from Whittaker [120]

The Clean Production Action's GreenScreen (GreenScreen) [122] on the other hand also identifies the human health and environmental hazard endpoints associated with a substance along with their level of hazards, but instead also consolidates the hazards into four benchmarks in order to rank the substances and help make better substitutions. As can be seen in Figure 4.7, the four benchmarks are:

- Benchmark 1: Avoid- Chemical of High Concern
- Benchmark 2: Use but Search for Safer Substitutes
- Benchmark 3: Use but Still Opportunity for Improvement
- Prefer- Safer Chemical

For example, a chemical that has very high persistence and very high bioaccumulation hazard endpoints will fall under Benchmark 1 (Figure 4.8: Benchmark 1, combination b) and therefore should not be used.



This chemical passes all of the criteria.

GREENSCREEN BENCHMARK-4

Low P* + Low B + Low T (Ecotoxicity, Group I, II and II* Human) + Low Physical Hazards (Flammability and Reactivity) + Low (additional ecotoxicity endpoints when available)

Prefer—Safer Chemical

If this chemical and its breakdown products pass all of these criteria, then move on to Benchmark 4.

GREENSCREEN BENCHMARK-3

a. Moderate P or Moderate B
b. Moderate Ecotoxicity
c. Moderate T (Group II or II* Human)
d. Moderate Flammability or Moderate Reactivity

Use but Still Opportunity for Improvement

If this chemical and its breakdown products pass all of these criteria, then move on to Benchmark 3.

GREENSCREEN BENCHMARK-2

a. Moderate P + Moderate B + Moderate T (Ecotoxicity or Group I, II, or II* Human)
b. High P + High B
c. High P + Moderate T (Ecotoxicity or Group I, II, or II* Human)
d. High B + Moderate T (Ecotoxicity or Group I, II, or II* Human)
e. Moderate T (Group I Human)
f. Very High T (Ecotoxicity or Group II Human) or High T (Group II* Human)
g. High Flammability or High Reactivity

Use but Search for Safer Substitutes

If this chemical and its breakdown products pass all of these criteria, then move on to Benchmark 2.

GREENSCREEN BENCHMARK-1

a. PBT = High P + High B + [very High T (Ecotoxicity or Group II Human) or High T (Group I or II* Human)]
b. vPvB = very High P + very High B
c. vPT = very High P + [very High T (Ecotoxicity or Group II Human) or High T (Group I or II* Human)]
d. vBT = very High B + [very High T (Ecotoxicity or Group II Human) or High T (Group I or II* Human)]
e. High T (Group I Human)

Avoid—Chemical of High Concern

BENCHMARK U

- Unspecified Due to Insufficient Data

ABBREVIATIONS

P	Persistence
B	Bioaccumulation
T	Human Toxicity and Ecotoxicity

Group I Human includes Carcinogenicity, Mutagenicity/Genotoxicity, Reproductive Toxicity, Developmental Toxicity (incl. Developmental Neurotoxicity), and Endocrine Activity.

Group II Human includes Acute Mammalian Toxicity, Systemic Toxicity/Organ Effects-Single Exposure, Neurotoxicity-Single Exposure, Eye Irritation and Skin Irritation.

Group II* Human includes Systemic Toxicity/Organ Effects-Repeated Exposure, Neurotoxicity-Repeated Exposure, Respiratory Sensitization, and Skin Sensitization. Immune System Effects are included in Systemic Toxicity/Organ Effects.

Ecotoxicity includes Acute Aquatic Toxicity and Chronic Aquatic Toxicity.

Note: The level of hazard indicated is the lowest hazard level at which a chemical would fail that criterion. However, if the chemical has a higher hazard level than what is listed (e.g. chemical is very High and the criterion is High), it would also fail that criterion.

* For inorganic chemicals with low chronic hazards, persistence alone will not be deemed problematic (see method documents).

Figure 4. 8 GreenScreen for Safer Chemcials benchmarks, from GreenScreen[122]

Multiple frameworks also exist for risk assessments. One such framework is the Global Product Strategy (GPS) International Council of Chemical Associations (ICCA) Guidance on Chemical Risk Assessment [123]. They advise experts to conduct a risk assessment, and their framework includes hazard characterization, exposure assessment and risk characterization. Figure 4.9 summarizes the eight-step framework proposed by the ICCA. Their online guide provides more assistance in conducting this assessment.

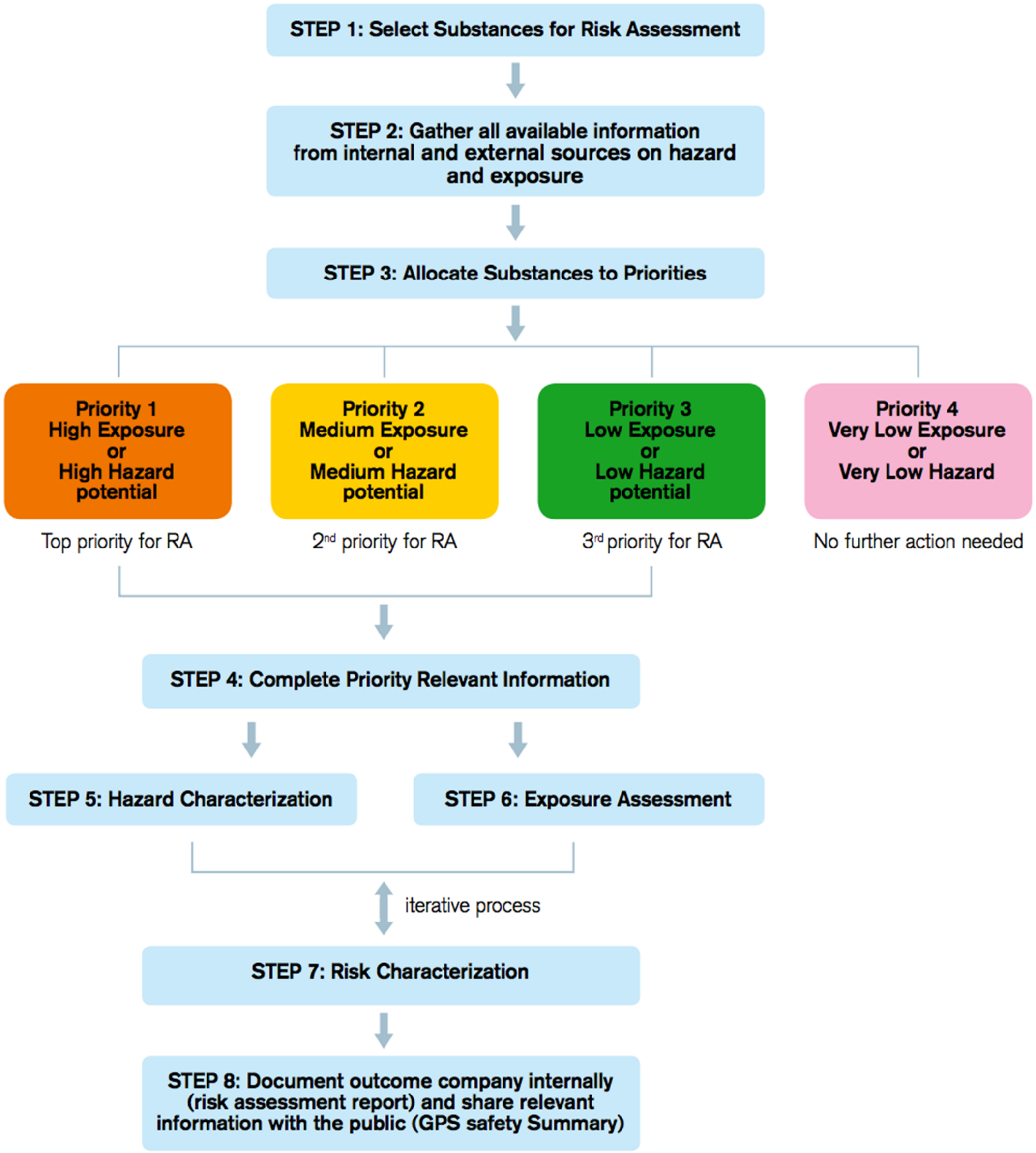


Figure 4. 9 GPS ICCA Guidance on Chemical Risk Assessment, from ICCA[123]

The US EPA outlines four steps to conduct a risk assessment. The first step involves hazard identification to examine the potential of a chemical to cause harm. The second step is to examine the dose-response relationship, the likelihood of the adverse effect (the response) to the amount and condition of exposure provided (the dose). The data to conduct this step is frequently missing and not available, thus data is often extrapolated from animal studies or observed estimations. The third step is to calculate the numerical estimation of exposure, otherwise known as an exposure assessment. It considers the magnitude, frequency, and duration of exposure and is more commonly estimated indirectly through measured chemical concentrations in the environment or by chemical transport models into the environment and estimate of human intake [112]. Finally, the last step is to characterize the risk and convey the overall conclusion or judgment using the information collected and assumptions made.

In addition, the U.S EPA Risk Screening Environmental Indicators Model (RSEI) is an online model that tracks toxic chemical releases and waste management activities from facilities across the US. The model is geographically based and incorporates data from the EPA's Toxic Release Inventory (TRI) to analyze the amount of toxic substances released, the risk factor associated with the chemical's fate and transport, the toxicity, the population exposed, and finally calculates a score. Yet, the model clearly states that it is a risk screening model that uses worst case assumptions but does not product a risk assessment for a facility.

Finally, the four primary paradigm frameworks used to conduct alternative assessments include the Lowell Center for Sustainable Production's Alternative Assessment Framework [40], BizNGO's Chemical Alternatives Assessment Protocol [124], EPA DfE's Alternative Assessment [125], and the Interstate Chemicals Clearinghouse (IC2) Guidance for Alternatives Assessment and Risk Reduction [126]. All the alternative assessment frameworks contain the same core elements: conducting a chemical hazard assessment, a life cycle assessment, and technical, social, and economic assessments [120]. Yet the frameworks differ in the amount of guidance they provide and sometimes exclude social assessments and life cycle assessments. Figures 4.10, 4.11, and 4.12 highlight the frameworks for the Lowell Center, BizNGO, and US EPA DfE's alternative assessments.

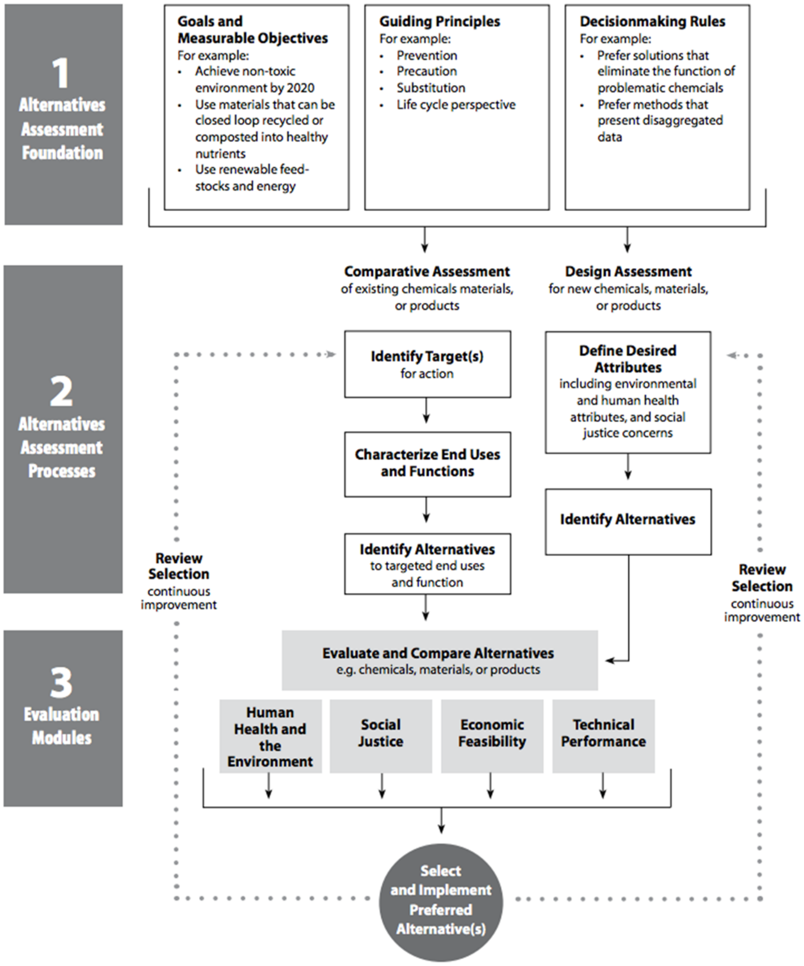


Figure 4. 10 Lowell Center for Sustainable Production Alternative Assessment Framework, from Rossi [40]

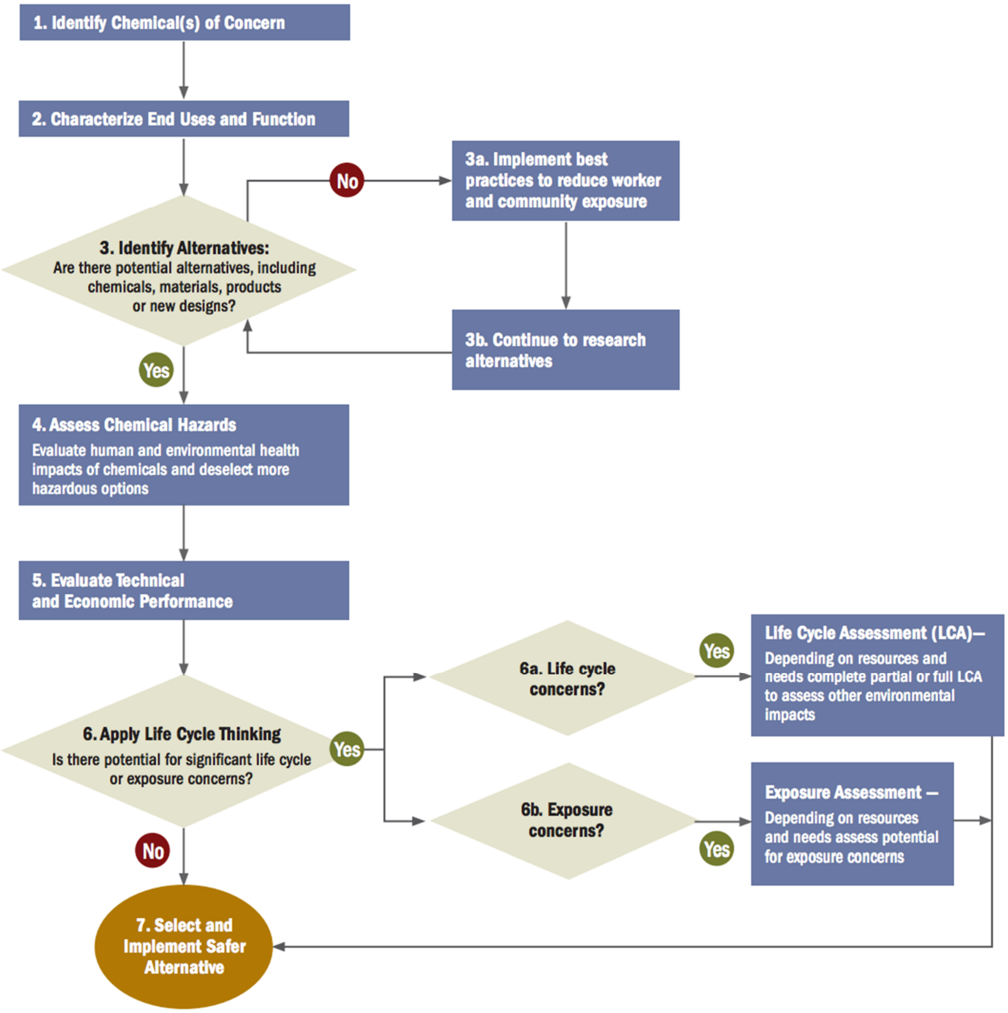
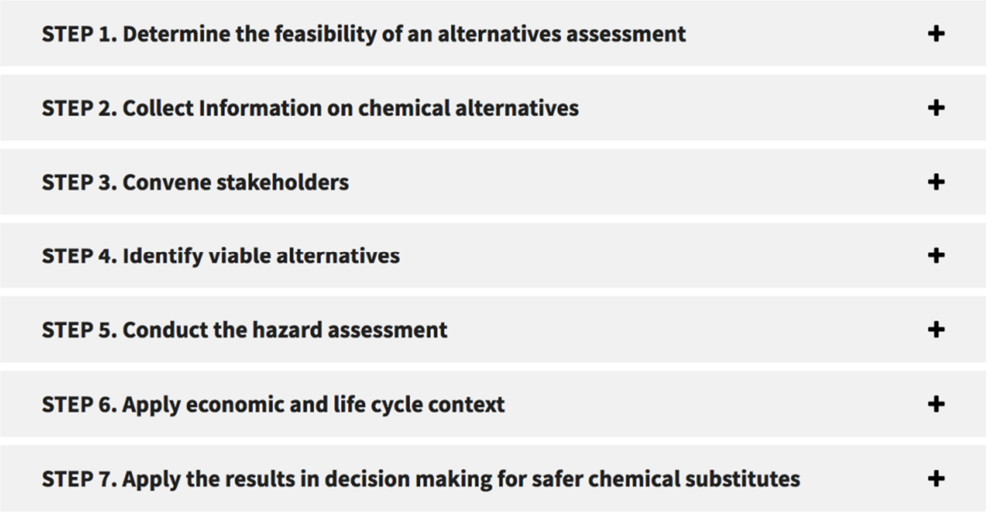


Figure 4. 11 BizNGO's Chemical Alternatives Assessment Protocol, from Rossi [124]



STEP 1. Determine the feasibility of an alternatives assessment

STEP 2. Collect Information on chemical alternatives

STEP 3. Convene stakeholders

STEP 4. Identify viable alternatives

STEP 5. Conduct the hazard assessment

STEP 6. Apply economic and life cycle context

STEP 7. Apply the results in decision making for safer chemical substitutes

Figure 4. 12 EPA DfE's Alternative Assessment, from EPA [125]

IC2's assessment however is much more complex and comprehensive. It provides three frameworks with seven modules that can be included in any one of the three frameworks. Not all modules need to be completed, and each module can also be completed to different levels [126]. The three frameworks are sequential, simultaneous and hybrid. Sequential frameworks evaluate the modules in a linear order and only continue with favorable alternatives as the evaluations proceed; simultaneous frameworks look at all the alternatives simultaneously; and finally, the hybrid frameworks screen first using a sequential framework then proceed with the simultaneous framework [126]. Yet all frameworks contain five steps (Figure 4.13): identify chemicals of concern, initial evaluation, scoping, identification of alternatives, evaluation of alternatives. In the scoping step, one of the three frameworks is chosen, whereas in the evaluation of alternatives step, the modules are chosen. The modules include a hazard module, performance evaluation module, cost and availability module, exposure assessment module, materials management module, social impact module, and a life cycle assessment module [126].

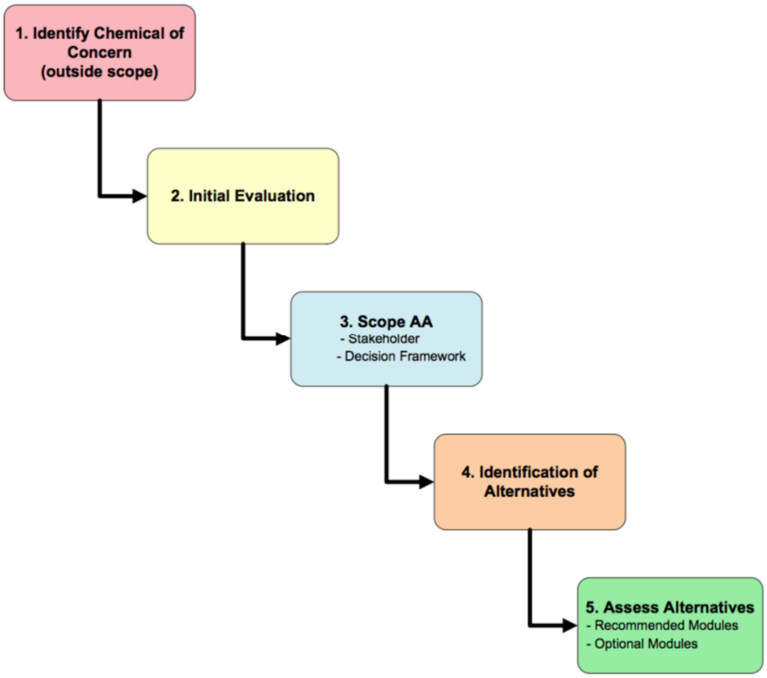


Figure 4. 13 IC2 Alternative Assessment Framework, from IC2[126]

Multiple other frameworks exist in addition to these frameworks presented above. Jacobs et al. [127] review twenty alternative assessment frameworks published from January 1990 to December 2004 in order to identify consistencies and differences in methods. They identified gaps in exposure characterization, life cycle assessment and decision analysis and concluded there is a need for greater consistency and evaluation and a need for greater research collaboration.

It is important to note, many tools provide a ranking or scoring method to evaluate chemicals based on their hazard endpoints. These systems are intended to be used as simple and quick methods to determine the health and environmental hazards posed by a substance [128]. Some systems categorize substances, such as grouping chemicals into classes of high, medium, or low concern. Scoring systems however derive one overall numerical score for a substance based on predetermined aggregation of the multiple hazard impacts. The results of the scoring systems are relative to each other [128]. Although these scoring or ranking systems help users make informed decisions, they can also mislead users. For example, using an equal weighting system for impacts may give a skewed score: a high score impact may hide the effect of a low score impact. In addition, a product that is intended to be in contact with a user's hand and has very high skin irritation and sensitization hazard may not be aware of this hazard due to its placement in the ranking or scoring system. Therefore, users need to understand how these ranking and scoring systems are implemented and obtain granularity on the impact data in order to make more informed decisions. Davis et al. [128] provide an evaluation of 51 ranking and scoring systems.

Therefore, although frameworks are important in order to guide assessment methodologies, their methodologies are not consistent. Some frameworks are theoretical, they tell a user what assessments must be done yet do not guide them on how to do it; while others are applied, they walk the user through the assessment steps and guidelines. Yet, in both these methodologies, the user has multiple decisions to make, often subjective. Thus, the same assessment methodology may result in different conclusions depending on the assumptions made. This does not provide a consist or thorough approach to evaluate material sustainability and is time consuming for engineers or designers to use when making material decisions.

Tools

Finally, tools provide the means to perform the assessment framework using the information from databases. Again, multiple tools exist, yet they can be generally categorized into life cycle assessment tools, hazard assessment tools, and consumer awareness tools.

Life cycle assessment tools perform an LCA of a product or service using different databases to conduct the impact assessment. Such LCA tools include Gabi, SimaPro, and UseTOX. Yet these tools lack a hazard assessment. While Gabi [129] and SimaPro [130] concentrate on analyzing carbon and water footprints, resources used, eco-designs along all aspects of the supply chain across life cycle stages of a product or service, USEtox [131] instead characterizes human and ecotoxicological impacts of chemicals, outputting fate and exposure data. USEtox is based on a scientific consensus model. Therefore, life cycle assessment tools do not evaluate all the environmental and human health impacts, rather they concentrate on one or the other.

LCA industry tools also exist such as the Higg Material Sustainability Index (MSI) tool. The MSI tool is a cradle-to-gate LCA assessment tool for the apparel and footwear industry. It aims to engage product design teams and global supply chains to make environmentally sustainable decisions about material use and provides information, compares materials, and allows users to create custom materials with specific production process, blends and chemistry. It analyzes the chemistry, global warming, water scarcity, and adiabatic resource depletion for each material.

Hazard assessment tools include GreenScreen (previously discussed), Column Model, and the Waste Minimization Prioritization Tool (WMPT), among others. These tools help users' asses the hazards related to the substances in their products. The Column Model developed by the German Institute of Occupational Safety of the Social Accident Insurance [132], divides hazards into 6 categories, or columns, and each column is further divided into cells or boxes according to the level of risk associated with the hazards. Therefore, substances are compared by hazard columns and their associated risks, yet this method is limited to the data that can be obtained. The WMPT [133] is an EPA tool that examines the potential chronic risk to human health and the environment from persistence, bioaccumulation, and toxicity hazards along with their quantities, and computes an overall score based on these factors to assist in decisions related to environmental contaminants. As can be seen, hazard assessment tools are often specific to certain hazards or certain products or regions, and do not use a uniform analysis.

Hazard assessment industry tools also exist. For example, "The Plastic Scorecard is a method for evaluating the chemical footprint of plastics and a guide for selecting safer alternatives [134]." The goal of the Plastic Scorecard is to help business select safer chemicals and encourage plastic manufacturers to use safer chemicals and limit the use of chemicals of high concern to human health and the environment in manufacturing and products which will ultimately create safer chemicals with better end of life management options. The Plastic Scorecard is a methodology that helps users identify and select plastics based on inherently less hazardous chemicals [134]. It evaluates chemical inputs into the manufacturing process, which include core chemicals, primary chemicals, intermediate chemicals, and monomers, then scores each stage of the manufacturing process based on the hazards of the input chemicals and then aggregates the scores into a single score that ranks between 0 (most hazardous) to 100 (most benign).

Finally, consumer awareness tools exist that help users determine the sustainability of their products to help make better shopping decisions. Yet since these tools are consumer facing, they address the sustainability of products after they have been made instead of during the design and production process. Thus, these tools cannot change the sustainability of the products that have been made. Such tools include GoodGuide and the Environmental Working Group (EWG). GoodGuide [135] rates personal care, food, household, and babies and kids' products, assigning each product in their database a health and performance score between 0 (low, or worst) to 10 (high, or best). The score is based on an algorithm that takes into account the human health impact of the ingredients in a product, data adequacy, other negative aspects such as regulatory restrictions on ingredients in the product, and product management, which relates to product safety and performance. EWG [136] have a set of criteria and evaluate products based on their ingredients and manufacturing processes. Products that meet their set of criteria are given an EWG Verified stamp, indicating they are safe. Although consumer awareness tools provide useful information for users, they do not address the safety of products before they are made and distributed among customers and are based on proprietary algorithms that cannot be used by product manufacturers before they are produced.

The above information highlighted databases, frameworks and tools that are available to help guide safer material selection in industry. Yet as discussed, each of these methods have limitations. Moreover, they are not specific to the case study for this research: additive manufacturing, although they can be used to help guide material selection in AM. The next section outlines the research on sustainable materials for AM.

4.3 Additive Manufacturing Material Sustainability Research

The databases, frameworks, and tools explained above are not specific to AM material sustainability, yet may influence material choice decisions if used. Others have tried to address the sustainability specifically related to additive manufacturing. Previously, most of the additive manufacturing sustainability studies concentrated on the electrical consumption of the machines during a process and/or at idle times, and thus calculated the environmental impact of the energy consumption such as carbon dioxide emissions. Yet, the focus of this research is on material sustainability used in 3D printing rather than the energy consumption of 3D printers and the environmental impacts associated with that. As materials develop for AM, it is important to emphasize the sustainability, environmental and human health hazards associated with materials with unknown compositions.

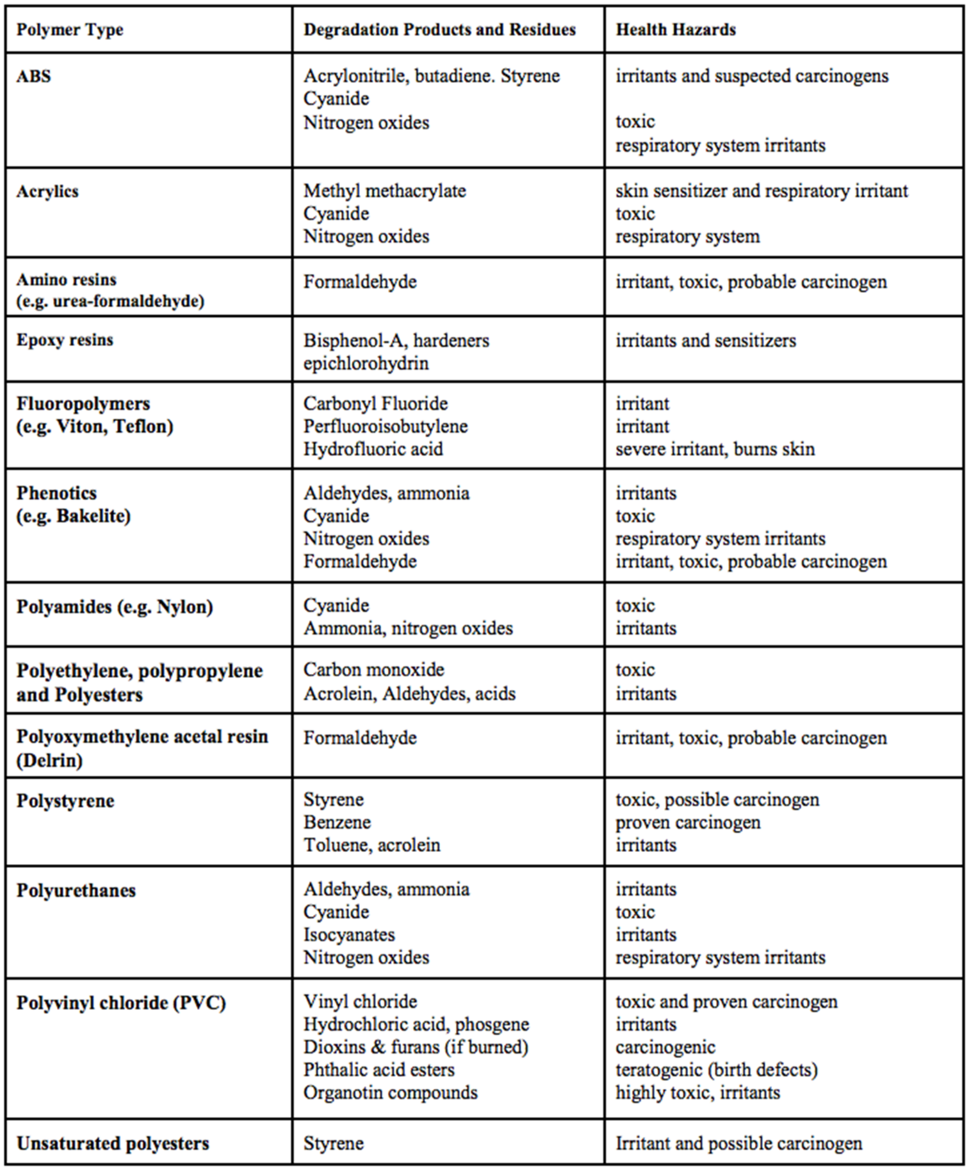
Bourhis et al. try to address the gap between materials and energy use and measure the environmental impact of additive manufacturing taking into account the electricity, material, and fluid consumption. Yet the model they created does not address the relationship between electricity, material, and fluid consumption, rather it estimates the consumption of each individually from a CAD file and aggregates the data together to measure the environmental impact. Faludi et al. [137] investigated the environmental impacts of 3D printing technologies along with the sustainability implications of materials that they use to print. They studied six 3D printers ranging from FDM printed with ABS, PET and PLA; polyjet printed with proprietary polymer; SLA also with printed with its polymer; and inkjet printers printed with salt and dextrose. They concluded that the environmental impacts are highly driven by the electricity consumption of the printers themselves, and not the materials. However, when looking at materials alone, there is a variation in environmental impacts from material choices. The inkjet printing in salt had the lowest impact, yet it significantly increased when an epoxy was added. Moreover, there was a variation in material environmental impacts between PET, PLA and ABS that were printed on FDM machines.

Oskui et al. [87] assessed the toxicity of 3D printed parts from fused deposition modeling and stereolithography printers by exposing zebrafish to the parts and monitored the rate of their survival, hatching, and developmental abnormalities. They printed with ABS material in the FDM printer and an unknown resin composition for the SLA printer. The results concluded that the SLA printer parts were significantly more toxic than the FDM printed parts and exposing the SLA part to ultraviolet light as a post-printing treatment would largely mitigate its toxicity. Post processing for FDM printers had little effect on toxicity.

Kim et al. [138] evaluated the hazardous emissions of ABS and PLA materials in FDM printing process using two different FDM printers. They concluded that FDM printing can be hazardous due to the high concentrations of emitted nanoparticles, carcinogenic aldehydes, phthalates, and volatile organic compounds. The particle concentration and emission rates were higher for ABS material than PLA material. Stephens et al. [139] studied the ultrafine particle emissions with two FDM printers using both ABS and PLA material. They also conclude ABS emissions are higher than that of PLA by an order of magnitude, yet both materials can be characterized as high emitters. In addition, Stephens et al. examined how the emissions can affect indoor air quality in office settings. They concluded that in a large well ventilated office, the UFA and VOC emissions from the FDM printer did not significantly increase the concentration in the air, yet they were easily detectable in a small unventilated room, even after 20 hours of printing. Steinle [140] also characterized the emissions from FDM printers using ABS and PLA material and focused on VOC and ultrafine aerosol (UFA) emissions as well as their emissions rates and concentrations. Finally, the most recent UFP and VOC emission research was conducted by Azimi et al. [141]. They tested five FDM printers using nine different filaments that included ABS, PLA, HIPS, nylon, laybrick, laywood, polycarbonate, PCTPE, and T-Glase. The highest UFP emissions resulted from ABS while the lowest from PLA. VOC emissions varied yet the top three highest emitted compounds accounted for 70% of all the VOC emissions from all the test cases. These three included caprolactam from nylon based, wood and brick filaments; styrene, a carcinogen, from ABS and HIPS filaments; and lactide from PLA filaments. Azimi et al. also look at the implications for human exposure and health effect in an office environment and conclude caprolactam concentration would exceed the recommended exposure limit (REL) by the California Office of Environmental Health Hazard Assessment (OEHHA), the styrene concentration would by 20 times higher than the highest concentration measured in a commercial building in the US, and UFP concentrations would be 10 times higher than a school's typical 8-hour average indoor concentration.

Moreover, the Canadian Auto Workers (CAW) [85] union published a list of hazardous products and residues from heating plastics to form final products and how they can affect the workers' health. Since FDM printers heat material filaments in order to print, the degradation of products listed by CAW in Table 4.1 are important to know.

Table 4. 1 Potential health hazards of plastics processing, from CAW [85]



Polymer Type	Degradation Products and Residues	Health Hazards
ABS	Acrylonitrile, butadiene. Styrene Cyanide Nitrogen oxides	irritants and suspected carcinogens toxic respiratory system irritants
Acrylics	Methyl methacrylate Cyanide Nitrogen oxides	skin sensitizer and respiratory irritant toxic respiratory system
Amino resins (e.g. urea-formaldehyde)	Formaldehyde	irritant, toxic, probable carcinogen
Epoxy resins	Bisphenol-A, hardeners epichlorohydrin	irritants and sensitizers
Fluoropolymers (e.g. Viton, Teflon)	Carbonyl Fluoride Perfluoroisobutylene Hydrofluoric acid	irritant irritant severe irritant, burns skin
Phenotics (e.g. Bakelite)	Aldehydes, ammonia Cyanide Nitrogen oxides Formaldehyde	irritants toxic respiratory system irritants irritant, toxic, probable carcinogen
Polyamides (e.g. Nylon)	Cyanide Ammonia, nitrogen oxides	toxic irritants
Polyethylene, polypropylene and Polyesters	Carbon monoxide Acrolein, Aldehydes, acids	toxic irritants
Polyoxymethylene acetal resin (Delrin)	Formaldehyde	irritant, toxic, probable carcinogen
Polystyrene	Styrene Benzene Toluene, acrolein	toxic, possible carcinogen proven carcinogen irritants
Polyurethanes	Aldehydes, ammonia Cyanide Isocyanates Nitrogen oxides	irritants toxic irritants respiratory system irritants
Polyvinyl chloride (PVC)	Vinyl chloride Hydrochloric acid, phosgene Dioxins & furans (if burned) Phthalic acid esters Organotin compounds	toxic and proven carcinogen irritants carcinogenic teratogenic (birth defects) highly toxic, irritants
Unsaturated polyesters	Styrene	Irritant and possible carcinogen

Huang et al. [142] study the current state and future potential of additive manufacturing. In the review, they highlight the need for a material database with the mechanical properties of the parts fabricated by AM and the need to understand the interaction between materials and the printing process parameters. In addition, they review the gaps in design tools for AM. They conclude that design tools must be developed that assess the lifecycle costs and the impacts of AM components and products as well as aid designers in exploring the AM space with regards to shape, property, processes and other variations.

Gebler et al. [143] provide a comprehensive assessment of 3D printing from a global sustainably perspective and quantifies cost reductions, energy savings and reduced carbon dioxide emissions using a top-down approach. Table 4.2 highlights the sustainability criteria they address in the paper, yet as can be seen, hazardous or toxic effects of 3D printing material on the human health or the environment are not taken into consideration.

Table 4. 2 Set of criteria for sustainability evaluation of 3D printing-induced sustainability implications, adapted from Gebler et al.[143]

Criterion	**Description**
Economy	
Market outlook	Estimated market potential in the time frame of assessment
Applications	Suitable applications for 3DP process
	Changes in production processes through 3DP
Supply chain management	Changes in supply chain structures
Production costs	Changes in costs per piece and process
Material costs	Changes in raw material purchase costs
Machinery costs	Purchasing prices of different additive manufacturing technology
Production time	Changes in production time per piece
Envrionment	
Resource demands	Changes of material inputs in comparison to subtractive processes
Process energy	Changes in energy requirements per piece
Process emissions	Changes in ambient process emissions
Life cycle energy	Changes in life cycle energy demands of a product
Life cycle emissions	Changes in life cycle ambient emissions of a product
Recyclable waste	Changes in amount and type of recylable waste
Non-recyclable waste	Changes in amount and type of non-recyclable waste
Society	
Development benefits	Sustainability for open srouces appropriate technologies (OSAT)
	Implicatiosn for self-directed sustainable development
Labor patterns	Changes in labour intensity, employment schemes, and types of work
Impacts	Social impacts generated through 3DP (positive and negative)
Acceptance	Socio-economic, community and market acceptance
Health	Changes in medical treatments or medical components
Ethics	Ethical questions on morality of stem cell technology
Copyright, patent and trade mark	Questions concerning copyrights/ shifts in
	Impacts of OSAT on patents/copyrights
Licensing	Shifts in licensing generated through OSAT applications
Product quality	Changes in product quality

Other studies have looked into the recycling of 3D printer filament to reduce material waste and costs. In this process, the waste material would be grinded and shredded then heated in order to melt the material and then extruded into a filament and spooled, ready to be reused in an FDM printer. One such study is currently being conducted in UC Berkeley by the 3D printer Filament Reclamation Project [144] team in order to decrease the amount of 3D printing plastic waste. Another study by Kreiger et al. [145] studied HDPE recycling and its effect on energy demand and greenhouse gas emissions. They compared centralized recycling systems in low and high population density areas to in home distributed recycling systems where the plastic is shredded and made into a filament. Even for the best-case scenario of a centralized recycling system, they concluded that recycling HDPE using a distributed system consumes less embodied energy.

In addition to these studies, companies have been motivated to address the negative human health and environmental impacts from 3D printing materials. For example, Carndo ChemRisk, a scientific consulting firm and Reed Smith, a law firm, held a joint 3D printing technical symposium [146] that addressed potential hazard considerations and 3D printer emissions, presented a framework for hazard identification, and presented bio-friendly alternatives to 3D printing materials. Moreover, Autodesk is aware of the toxic hazards associated with resin used for SLA printing and have been conducting research using the concept of biomimicry in order to formulate a non-toxic resin. They came up with three approaches to improve the resin hazard profile: replace the photoinitiator, modify the resin acrylates, and create an entirely new resin [147].

Yet, these studies all cover a small aspect of material sustainability, they mostly focus on toxicity and emissions of materials and do not study how the data can be integrated and used to influence the material decision making process. In addition, Huang et al. touched on the idea of the need to integrate material properties and process interactions into a database while Gilber et al. highlighted the importance of quantifying cost savings. Yet again, the studies mentioned here are missing the important considerations for making material decisions: price and performance. As suggested in the interviews, without adding these two aspects, material decision making will not change or be influenced since material decisions are currently only based primarily on price and performance. Moreover, material decisions are made quickly, and presenting designers and engineers with multiple conflicting health and environmental impact data points hinders the process and make it anything but quick. Therefore, an emphasis on integrating the trade-offs between price, performance and material health and environmental impacts to influence better material decisions must be studied.

4.4 Additive Manufacturing Focused Interviews

Chapter 2 reported on the results of empirical research to understand generally how materials choices are made in industry. It provided the broader context in which materials decisions are made, the organizational complexity surrounding those decisions and the lack of use of tools and databases. This section, following the general descriptions of standards, regulations, databases, frameworks and tools that have been developed for the AM industry to date, describes the results of additional empirical research to understand selection of AM materials in industry.

To understand material selection within the additive manufacturing industry, an additional set of interviews and a survey were conducted with individuals who work with 3D printing. In person interviews, phone interviews and an online survey were used. The first portion of the interview and survey was to understand the space the individual works in, what type of products they print and the individual’s role within the company. The second portion focused on what 3D printer technology is used within their company, why those technologies were chosen, how many printers are in their facility and how they are distributed. It also asked what types of materials are being printed, if they experience any fumes from the printers and if the printers have any exhaust systems to get rid of the fumes. The third segment concentrated on the importance of material characteristics and mechanical properties during the selection of materials for printing. Since material performance properties and characteristics were important and most frequently cited during the initial interviews on material selection (discussed in Chapter 2), the goal of these questions was to understand which specific characteristics and properties designers are concerned with and considered important for material selection in the 3D printing industry. Finally, the last section of the interview and survey concentrated on how material vendors are chosen, who selects these vendors, and if any internal or external guidelines, standards or regulations affect their material purchases along with their awareness of material hazards. The survey used can be seen in AppendixA.4.

The in-person and phone interviews asked the same questions as the survey. Only two respondents answered the online survey although a total of eight interviews were conducted. Two interviewees are CEO's of 3D printing manufacturing companies, three are in the environmental, health and safety department in their workplace, two work in a design innovation lab as a technical lead and a design specialist, and the last interviewee is the CEO of a design consulting firm. The 3D printing manufacturing companies print customized products such as awards, keychains, hardware components, brackets, enclosures and other products and prototypes. The design consulting firm mostly works on customized furniture, food packaging, medical devices and other range of products.

Interview Responses and Results

The most commonly reported 3D printer technologies used are fused deposition modeling (FDM) and stereolithography (SLA), both discussed in Chapter 3. FDM is consistently chosen due to its price point and its ability to print with multiple materials, and represents the most dominant technology chosen. SLA is used for more advanced and specific objects that need better accuracy and material finish. The number of 3D printers in one facility ranged from 5 to 160; the design settings had fewer printers, while the production operations had more. They were all distributed within the same location except for one lab that separated FDM and SLA printers onto different floors. The reason for the separation is due to safety and health considerations and for experimental testing with novel material on the FDM and SLA printers. Such novel materials included PLA merged with wood fill or metal fill that have unknown health hazards.

Printing material varied from respondent to respondent. Only two respondents print with ABS while the others specifically reported that they avoid this material due to multiple studies that indicate high levels of particulate data such as volatile organic compounds (VOCs) and ultra-fine particles (UFP). The respondents that use ABS indicated they use it to meet the performance requirements of the printed product; such as if the function requires strength or if it will be used as an engineering prototype. One respondent noticed a pungent smell while printing with ABS yet indicated they did not install specific ventilation systems in order to address this problem, rather they rely on the air exchange rate within their facility. Ideally, they would like to print close to an open ventilation system (such as a window), but temperature fluctuations affect the final product print complicating that choice.

PLA was the most commonly cited material used for 3D printing due to its low cost and low off gassing of particulate data. It is made of plant-based resources such as corn starch or sugar cane and is biodegradable. The biggest drawback to PLA is its functionality; it is stiffer and harder causing it to be more brittle and it deforms and warps easily at high temperatures.

Other materials mentioned were TPU, nylon, polypropylene and PHA although all these materials were limited in use and were more experimental. Metals and ceramics were also mentioned as more advanced materials that can be used and have better output quality yet are not used in the consumer market, but only in the industrial market. Most interviewees suggested they use standard materials and stock only what users request unless asked to experiment with new materials.

Consistency and quality, material performance, color and cost were among the four top characteristics used when making material decisions. Filament consistency such as uniform filament diameters and homogenous material quality is important to get reliable prints, minimize failed parts and reduce clogging of the printers. Other less frequently mentioned characteristics used to choose materials are good MSDS (Materials Safety Data Sheets) documentation, regulatory compliance, and personal safety and environmental impacts.

Important material mechanical properties that were stated by all the interviews included impact strength, moisture absorption and heat deflection. Companies try to incentivize their clients to use materials that have been opened from their packaging due to moisture absorption. The longer the material has been out, the more moisture it is likely to absorb and the harder it is to print with. Other mechanical properties included density, finish and flexibility. Density is needed for the use of extruders and not for printing a product. Other characteristics that may be needed are specific and unique to the application of the product such as the material's ability to meet food safety, medical, conductivity, magnetic, and radiation resistant requirements. Only one respondent works with an external testing lab to test the mechanical properties of their printed material whereas another company encourages their users to follow the trial and error methodology when their print fails. Table 4.3 summarizes the criteria used for material decisions in the 3D printing industry.

Table 4. 3 Material selection criteria in the 3D printing industry

Performance	Aesthetics	Cost	Other
Material consistency and uniform diameter; mechanical properties; reliability; safety; quality	Color; finish; feel; opacity; reflectivity	Materials	MSDS documentation; fast delivery; custom compound batches

Taking these characteristics into consideration, AM material vendors are chosen based on material consistency, availability of colors, reliability, cost, and fast delivery. Other criteria included good MSDS documentation and the ability to procure custom compounds in small batches. Most vendors are chosen by the printer operators yet one interviewee indicated their company has internal guidelines for evaluation processes before integrating a new material or supplier.

Finally, when asked about external or internal guidelines, standards or regulations that affect material purchase and awareness of material hazards all interviewees responded by stating they follow OSHA facility requirements and are not aware of other standards or regulations in the industry. One company also noted they follow the guidelines indicated by MSDS sheets and their internal environmental, health and safety department (discussed below). All interviewees are aware of potential toxic fumes that are emitted by printing materials yet almost none of them have specific exhaust systems, fume hoods or snorkels to get rid of the fumes. Only one stated they have installed fume hoods and enclosures for their SLA printers and not FDM printers due to the wider variety of materials printed along with their unknown inherent hazards. Moreover, they mentioned they are aware that material and resins must be mixed in printer trays and are toxic before curing. Finally, although no specific systems are installed, one company does test and measure their facility's air quality for UFP and VOC emissions and reported healthy numbers. Other hazards mentioned included concern with part cleaning due to solvents and cutting tools as well as possible burns that are addressed with protective equipment.

The interviewees from the environmental, health and safety (EHS) department are in charge of procurement of 3D printers and materials, laboratory safety and training, as well as conducting hazard exposure assessments. If a facility they are to manage is new, then procurement is the simplest. The researchers in the facility specify what they need and contact the necessary manufacturers. The EHS department then works with the manufacturers and indicate the specifics of the laboratory: area of the space, the occupancy, and the mechanical air exchange rates within the lab and building, which is dictated by the city building codes. The manufacturers and vendors then recommend the necessary ventilation requirements for the equipment. After this step is completed, EHS installs emergency eye wash and showers and trains the laboratory on safety, chemical storage containers, and disposal of hazardous substances and provides onsite safety standards. The laboratory or facility then receives a validation stamp by both the EHS department and the city fire marshal. Retrofitting a lab is more complicated because buildings typically recirculate the air for energy efficiency yet do not want to circulate particulate matter from 3D printing.

As mentioned, EHS conducts site preparations and training for each lab on material handling and waste. Material procurement usually passes through the EHS electronic ordering system unless it contains EHS trigger points such as toxic materials, drugs or biohazard materials. In that case, EHS verifies the order with the laboratory and makes sure the order will be safe. Within a 3D printing lab, EHS is concerned with loading dry mixes, dust and powders (such as silicon alumina particles) thus recommends using masks and fume hoods. Furthermore, they are concerned with bath solutions and solvents (such as sodium hydroxide) that are typically used for post processing 3D printed products. These solvents pose a hazard both during their use and after, since they may be corrosive and cannot be drained. Drain disposal has a pH restriction that is dictated by the municipality.

Finally, while printing, off gassing is a concern for EHS. Although they do meet indoor air ventilation requirements, they may add extra fume hoods or snorkels depending on the materials being printed. They also conduct exposure assessments for VOC and UFP emissions. The city also has air district emission compliance and thresholds. EHS works to ensure these standards are met, although they do not always measure exhaust emissions themselves.

The 3D printing specific interviews highlighted that material decisions are based on the same set of metrics that are used across industries: performance, aesthetics and costs, although there is some variation in the metrics under performance (Table 4.3). Yet in addition to those criteria, good documentation for material MSDS sheets seems to play a role in choosing a material supplier. It is interesting to note that although the people interviewed in the 3D printing industry are aware of some of the toxic off gassing related to printing with FDM and the toxic resins before curing used in the SLA printers, no specific safety systems have been installed to address these hazards. Moreover, there are material regulatory requirements specific to the products they are printing for certain industries, yet in general, they are not aware of regulations or standards that directly affect their business.

The interviews indicated there are no tools or databases specifically used to select materials for 3D printing. Moreover, many voiced concern over the hazards of the materials they are printing yet did not know what they are and how to address them.

A platform that combines material performance properties, costs, aesthetics, and hazards is needed in order to inform better material decision making. The rest of this research aims to addresses this need by collecting and synthesizing material data and creating a tool that highlights the tradeoffs, specifically for the additive manufacturing industry.

Chapter 5

Material Data Collection

Chapter 2 reported the finding that materials selection decisions are made largely on the basis of cost, performance and aesthetics. Chapter 4 probed more deeply into materials selection in the Additive Manufacturing (AM) space, specifically identifying consistency and quality, material performance, color and cost as the criteria on which AM materials are chosen. Sustainability, specifically environmental performance, is rarely considered unless it is part of a company's core values. In cases in which it is considered, it is often seen as in conflict with achieving cost and performance objectives.

The goal of the research presented in this chapter and the next is to find an objective approach for integrating sustainability into the materials choice process by designing a tool that allows for the collective evaluation of costs, performance, aesthetics and sustainability. The primary aesthetics consideration in the AM world for this research is limited to color, opacity and reflectivity and are included in the aesthetics category in this chapter.

Figure 5.1 highlights the relationship between the inputs users base their material selection on, the process to translate the inputs to outputs, in this case the process is a tool that was created in Excel, and the outputs that map the trade-offs between materials that meet the user's input requirements. Yet the process that converts inputs to outputs requires data in order to translate the information and search for materials that meet the user's needs.

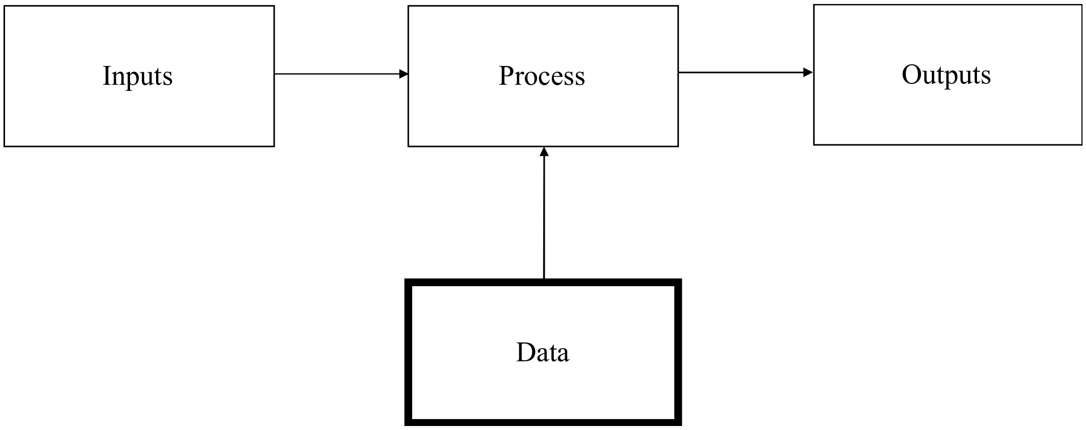


Figure 5. 1 Relationship between user inputs, process, outputs, and data to inform material selection

The tool will be presented in the next chapter. This chapter focuses on the all-important question of where one goes to collect all of the data needed to populate a tool, and ultimately to make a materials choice decision. It will make clear the complexity of gathering the required data, resolving inconsistencies in the data, and interpreting the results of the data collected.

In order to evaluate cost, performance, aesthetics and sustainability, a wide range of data had to be gathered. That required first bounding the problem space even more tightly to focus on materials that are used for FDM printers. FDM printers are the most commonly used printers on the market with over 50% of the market [148], [149], so this study would have the widest impact. Thirty-seven material filaments were studied with varying base compositions. Table 5.1 highlights the filaments studied. The filament materials chosen for this study include the most commonly used FDM material bases. In addition, many small and/or local filament manufacturers exist, yet for this study the most common material manufacturers reported on the material supplier's website were used. Table 5.1 also outlines the material suppliers of the filaments under investigation.

Table 5. 1 3D printing material filament manufacturers and base material of filaments under examination

3D Printing Material Filament Manufacturers
ColorFabb
Kai Parthy
MatterHackers
NinjaTek
Polymaker
Proto-Pasta
Taulman 3D

BASE MATERIALS	
ABS	PLA
HIPS	PLA & Brass
TPU	PLA & Bronze
TPE	PLA & Copper
Polycarbonate	PLA & Wood
PETG	PLA & PHA
PETG & 20% Milled Carbon Fiber	PLA & Steel
Nylon	Nylon & TPE

In order to collect the data, multiple sources were used, each to obtain specific information. Material costs and aesthetics data were obtained from a material supplier website. Performance data was collected from each material's manufacturer website, and if the data was unavailable then it was collected from a MSDS or material supplier's website or even research papers. Multiple inconsistencies appeared during this process due to the varying use of terminology and units reported. Finally, sustainability data was collected from The Pharos Project, an online hazard database, MSDS, and from research papers. The collection process for performance and sustainability data are the most difficult between the four sections due to the numerous data sources, inconsistencies in reporting, and incomplete reporting of information. A more detailed description of the collection process is described below. The process highlights how difficult it would be for an individual designer or engineer to capture all the necessary material data and interpret it in a timely manner in order to make more informed material decisions.

5.1 Cost Data Collection

Costs of the 36 filaments were obtained from the material supplier website, MatterHackers [150]. MatterHackers sells a variety of 3D printers, over 350 filaments from multiple material manufacturers, accessories and software specifically related to 3D printing. Due to their sizable filament collection, obtaining prices from MatterHackers provided a baseline price from one supplier for this study. The costs of the materials were gathered on June 16, 2016

Although cost collection data for this research was straightforward, it does typically have variability and complexity. Variability in pricing arises from purchasing material during different times of the year and from different material suppliers. For example, the Bendalay filament material on MatterHackers is currently (04/2017) selling for $96/kg versus $152/kg when the data was first collected, whereas ColorFabb XT CF20 Carbon filament material is now $73/kg but was $104/kg when the material price was initially collected [150]. Therefore, in order to keep consistent with the costs of materials, cost data must be collected and updated almost daily. In addition, using different material suppliers may result in different pricing for the same material.

Moreover, there is a layer of complexity to material cost data collection. The costs collected for this study are retail prices, yet companies may purchase materials at wholesale prices or even arrange contracts between them and the material suppliers for discounted rates that cannot be captured in this study. Thus, while this study pulls the cost data from a single site in order to provide consistency across the materials, the costs may not be the actual price a company would pay. However, this data is relatively easy for a procurement group to obtain at a company.

5.2 Performance Data Collection

Performance data included material descriptions, mechanical properties and printing guidelines. The properties were divided into two categories: Those properties that are important to designers and engineers while making material decisions as discerned from the interview data and described in Chapter 4, and other properties that are reported on the material technical specification sheets.

Although the other properties that are reported on the technical specification sheets were not reported to be as important to material decision making, they were kept in order to provide a complete view of the data available on a material. In total, there were 22 properties reported, although not all information could be obtained for each material. In addition to material property information, interviewees stressed the importance of knowing the description of the materials they are using such as what their base material are and their typical use case scenarios. Table 5.2 highlights the description and mechanical properties and printing guidelines the interviewees considered to be important when making decisions relating to materials in the 3D printing industry and the other reported properties that were included.

Table 5. 2 Performance data gathered on each material

Description
Material
Base Material
Composition
Typical Use

Important Mechanical Properties
Melting Temperature [C]
Tg Glass Transition Temperature [C]
Density [g/cm3]
Ultimate Tensile Strength [MPa]
Yield Tensile Strength [MPa]
Moisture Absorption [%]
Ultimate Elongation [%]
Heat Deflection Temperature [C]

Important Printing Guidelines
Printing Temperature [C]
Print Bed Temperature [C]
Printing Speed [mm/s]

Other Mechanical Properties
Solubility
Young’s Modulus [MPa]
Mold Shrinkage [%]
Melt Index [g/10 min]
Shore Hardness [A]
Flexural Modulus [MPa]
Impact Strength [kJ/m2]
Tolerance [mm]
Thermal Degradation [C]
Infill Speeds [mm/s]
Abrasion Resistance [g]

Collecting material performance data proved to be tedious and complex as explained below. Unlike cost data, material performance data does not have much variability; once it is tested, the data is certain, but it is no less complex. The data is often incomplete or reported in inconsistent units, properties, and testing procedures.

Dispersed Data Sources

The biggest challenge in gathering this data was inconsistency in the data. The data was dispersed, so in order to collect the data, multiple sources had to be utilized. The primary sources of data included: technical specification or data sheets that each material manufacturer reported on their own websites or that were outsourced by third part distributors; MSDS sheets produced by either the material manufacturers or third party distributors; data reported by material supplier’s websites; and if none had the data, then research papers were used.

It is important to distinguish between these sources. Technical specification or data sheets are documents that outline the technical and performance characteristics of a product [151], [152]. For example, the technical specification sheets of a material may contain all the mechanical, physical, and thermal properties of a material. Material Safety Data Sheets (MSDS) on the other hand, outline the occupational safety and health hazards associated with a material [153]. Typically, MSDS identify hazards of a material, precautions for safe handling and storage, and recommended exposure controls and personal protection, among other data that will be discussed below.

The description of the materials was collected from the MatterHackers website [150]. They reported the base material of the filaments, their typical use case applications, and other adjectives used to describe the materials (e.g., flexible, tough, abrasion resistant, chemical resistant). The adjectives were rarely quantified in any way, requiring capture and comparison of adjectives across data sources. Although MatterHackers also report printing guidelines for materials, the guidelines are based on their opinion of optimal printing temperatures and speeds rather than on the material supplier's recommendations. In addition, some of the materials on MatterHackers have a few mechanical properties reported while others do not. Therefore, mechanical properties and printing guidelines from MatterHackers were not collected and used in order to remain consistent with the material manufacturers recommendations.

After the initial description of the material was collected, printing and mechanical performance properties were gathered. To obtain this data, the technical data sheets that each material manufacturer supplies were used [152]–[156]. This involved going to the material manufacturer website, searching for the specific material of interest, and then finding the data sheet they provide. It was apparent that most of the material manufacturers outsourced their data testing to third party companies to provide this information and sometimes one material manufacturing company would outsource their data testing to multiple third party companies. Therefore, the data sheets from one material manufacturer could contain different data or different representations of the data.

If the information needed was not in the manufacturer's technical data sheet, then the material safety data sheets (MSDS) were used [152]–[156]. Again, in order to find these, the specific material within the manufacturer's website had to be searched for and then the MSDS would be pulled from there. Yet, if the MSDS did not have the information, then the data was searched for on the actual material manufacturer's website. This may seem odd, yet some material manufacturers reported the performance data of a material on their webpage instead of a technical data sheet or MSDS.

Finally, if information was still missing, then the data reported by MatterHackers was used [150]. In five material cases where the data was still not enough, the information was then obtained from a research paper that tested specific material properties of the filament material of interest [159].

The reason for obtaining the data in this order was to provide consistency with the properties being reported. Since the manufacturers of the material are assumed to have the best know how of using what they produce and supply, data reported from their technical data sheets, MSDS, and website were first priority. Other sources were then considered when data was not available. This collection process shows how time consuming it may be for an individual engineer or designer to obtain material information when trying to compare a minimum of two materials for a product.

Incoherent Properties

As stated above, multiple sources were utilized in order to obtain all the material data description and properties needed to form a tool. Moreover, material manufacturers often outsourced the creation of their technical data sheets to multiple third party companies who tested their performance properties. This dispersed data created another complexity to the data collection, incoherent data properties.

One of the large incoherencies in the data was the multiple terminologies used for the same property. In some cases, there were over 4 terms used for the same property. Table 5.3 highlights the terminologies used per property. The second largest source of incoherencies in the data was the different reported units of measurement for the properties, which was easier to solve. Some units were reported in metric while others in imperial units. To create a consistent data base, units had to be converted. The metric system was used.

Table 5. 3 Property synonyms, by row

Property	Synonym	Synonym	Synonym
Density	Speficic gravity		
Melt flow rate	Melt index		
Flexural modulus	Bending modulus		
Flexural strength	Bending strength		
Ultimate Elongation	Elongation at break		
Mold shrinkage percentage	Linear mold shirnkage	Shrinkage- in/in	
Tensile strength, yeild	Tensile stress at yield	Tensile stress	
Moisture content	Water abosprtion at saturation, 23C %	Humididty absportion %	
Tensile strength, ultimate	Tensile strength	Tensile strength maximum	Tensile stress at break
Notched impact strength	IZOD Impact strength, notched	IZOD impact strength, unnotched	Impact Strength
Young's Modulus	Modolus of Elasticity	Modulus PSI	Tensile Modulus PSI

In addition, different testing methodologies were reported for the same property that resulted in different reporting data. For example, izod impact strength is an ASTMD256 standard for determining the impact resistance of materials. Yet it can be reported both as energy lost per unit thickness at the notch or as energy lost per unit-cross sectional area at the notch [160]. Moreover, in Europe, ISO 180 test methods are used instead to evaluate the cross-sectional area of the notch. Furthermore, some impact strengths were reported as notched while others were unnotched.

Other differences were in hardness, some reported the data as a shore hardness with a measurement unit scale of A while others measured Rockwell hardness on an R scale. The hardness test is used to measure the resistance of plastics toward indentation, where an A scale is used for ‘softer’ plastics and rubbers and the Rockwell test and R scale are used for ‘harder’ plastics [161], [162].

Other discrepancies were found in the testing methodology for moisture absorption and density. While most followed ASTM D570 testing standards and thermogravimetric method for moisture, and ASTM D792 for density, PolyMaker [156] sometimes cited their testing methodology as “custom method” and Taulman [157] did not specify their testing methodology.

Finally, the biggest difference in testing methodology was for materials made by Colorfabb [154]. While most reported ASTM testing properties, ColorFabb reported properties according to ISO testing methodologies including mechanical properties, impact strength, shore hardness, density, and melt flow rate. For example, mechanical properties such as yield and ultimate tensile strength, tensile modulus, elongation at yield and at break, and toughness were reported according to ASTM 638 test methods by almost all the material manufacturers, except for Colorfabb, which reported according to ISO 527.

Other incoherencies were the reporting of wide data ranges. Data ranges were used for filament melting temperatures, densities, young's modulus and ultimate elongation. Other ranges were reported for expected properties such as printing temperatures and print bed temperatures. For example, Polymaker's PolyPlus PLA filament had a young's modulus range of 2636 ± 330 MPa which is a considerable range when trying to determine a material's elastic deformation. In addition, the same material's printing temperature was listed to be between 195-230 °C and printing speed between 40-90 mm/s. Although the printing property ranges are typical, an explanation of an optimal combination or the performance of the extremities of the ranges are not given.

Finally, different sources such as the material manufacturer website and MatterHackers often reported different data for the same printing guidelines. The reasoning behind this is that material manufacturers often want to provide a complete overview of the range of printing possibilities for a material while a material supplier such as MatterHackers has tested the best printing range of the material, and so limits its reporting to that range. For example, MatterHackers reported a printing temperature for the Polymaker's PolyPlus PLA filament of 190-210 °C if the printer has a heated bed and 210-230 °C if it does not. Although this range matches that of the range reported by Polymaker, MatterHackers provide a more thorough explanation of what range to use. Yet in other cases, such as NinjaTek's Semiflex filament material, NinjaTek reports a printing temperature of 225- 235 °C whereas MatterHackers suggests a printing temperature range of 210-225 °C. This adds yet another level of complexity to understanding the data.

Although it is difficult to recommend what data set to use, if a user is not an expert in 3D printing, it may be beneficial to access a material supplier website such as that of MatterHackers first, in order to obtain quick data on the optimal use of the material.

Data Cut Off

Although all the available data on a material were collected and stored in the database, there were multiple data gaps in the information available. Thus, in order to create a simple search tool with enough property information yet not overcrowd the interface with possibilities, only the properties with over 50% of material data reported were included in the search tool. Fortunately, the properties reported on the tool also aligned with the description, important mechanical properties and important printing guidelines used for material decisions indicated by the user interviews except for two mechanical properties; moisture absorption and heat deflection. Only three out of the 26 materials reported moisture absorption and only five out of the 26 material reported heat deflection.

5.3 Aesthetics Data Collection

Aesthetics data collection for the materials were limited to color, opacity and reflectivity. The data was collected from the material supplier's website, MatterHackers [150]. Not all the materials listed had information on their opacity and reflectivity, yet when they did, they were added to material database. The collection of color availability had some nuances such as distinguishing between “green, grass green, lime green” or “fire red and red” yet the data collection was not complex.

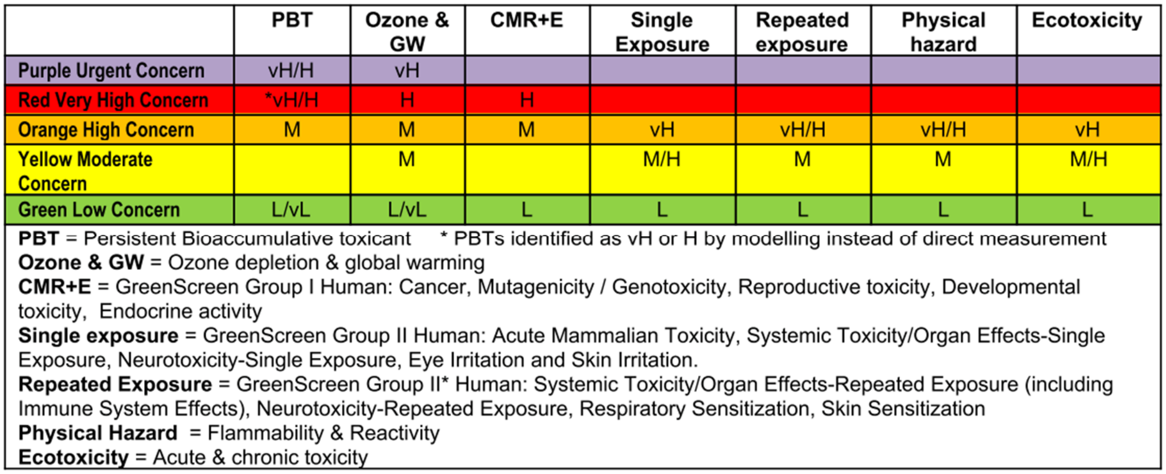
5.4 Sustainability Data Collection

In order to incorporate sustainability data into the tool, human health and environmental hazards were collected from multiple sources including The Pharos Project (Pharos), MSDS sheets, and academic research studies. Before presenting the data collection from each of those sources, there is a brief description of the boundary for the chemical hazard assessment performed by Pharos.

System Boundary Using Pharos

Pharos [163] was used for the majority of hazard data collection as it provides one of the most comprehensive databases of information in one location pertaining to both general information such as synonyms and descriptions, as well as hazard information (refer to Chapter 4 for more information on Pharos and hazard assessments). In addition to providing this information, Pharos goes one step further and categorizes the hazard into a priority level to indicate the urgency of avoiding the use of a chemical [117].

Pharos indicates the hazard endpoint, severity level, and priority level for each chemical and material. The priority level for each hazard is based on rankings in the GreenScreen for Safer Chemicals Protocol, discussed in Chapter 4. It ranks a high persistent or bio-accumulative toxicant as the highest priority level and urgent concern. A high carcinogen, mutagenicity, reproductive toxicity and any hazard related to a chronic disease with irreversible damage will then be the next highest priority level, indicated as very high concern. A respiratory sensitizer hazard will follow as a high concern, and finally a high skin irritant will be ranked as a moderate concern. A low concern material is a material that has been studied and not found to cause specific health impacts under consideration [117]. Figure 5.2 highlights the priority levels according to the endpoints and their severity.



	PBT	Ozone & GW	CMR+E	Single Exposure	Repeated exposure	Physical hazard	Ecotoxicity
Purple Urgent Concern	vH/H	vH					
Red Very High Concern	*vH/H	H	H				
Orange High Concern	M	M	M	vH	vH/H	vH/H	vH
Yellow Moderate Concern		M		M/H	M	M	M/H
Green Low Concern	L/vL	L/vL	L	L	L	L	L

PBT = Persistent Bioaccumulative toxicant * PBTs identified as vH or H by modelling instead of direct measurement
Ozone & GW = Ozone depletion & global warming
CMR+E = GreenScreen Group I Human: Cancer, Mutagenicity / Genotoxicity, Reproductive toxicity, Developmental toxicity, Endocrine activity
Single exposure = GreenScreen Group II Human: Acute Mammalian Toxicity, Systemic Toxicity/Organ Effects-Single Exposure, Neurotoxicity-Single Exposure, Eye Irritation and Skin Irritation.
Repeated Exposure = GreenScreen Group II* Human: Systemic Toxicity/Organ Effects-Repeated Exposure (including Immune System Effects), Neurotoxicity-Repeated Exposure, Respiratory Sensitization, Skin Sensitization
Physical Hazard = Flammability & Reactivity
Ecotoxicity = Acute & chronic toxicity

Figure 5. 2 Priority hazard levels, from Pharos [117]

Moreover, Pharos specifies if the hazard is from the substance or is a residual hazard. Residual hazards are due to chemical residuals from the manufacturing process of the substance. Residual process chemicals that are evaluated by Pharos include monomers, catalysts, non-reactive additives, pollutants and contaminants, and other known residuals [117]. The definition of each of these process chemicals can be found in Appendix A.5. Thus, Pharos analyzes the process chemistry (formerly referred to as the life cycle) of the chemical and material. It looks at the upstream chemicals used to manufacture the material, as well as their function and frequency of use in the process. The process chemicals are further divided into three categories, "known and potential residuals" that are used to make the chemical and likely to be present as residuals, "other" are chemicals that are used but less likely to be present as residuals and "used in the process chemistry of" for chemicals downstream that are synthesized using the chemical in question [117].

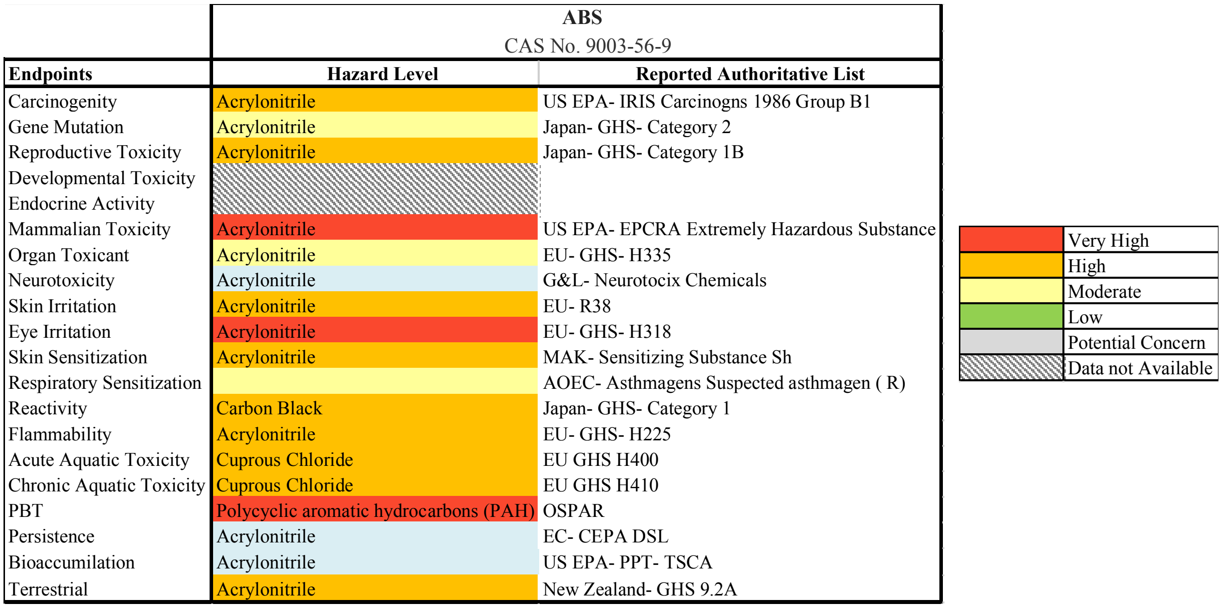
For this research, the system boundary was limited to the hazard levels reported by governing bodies and scientific agencies, and did not include the priority levels that Pharos designates. This was done as to not add an additional layer of data that is subjective to Pharos. Moreover, direct substance hazards were always reported first, and if data was missing then residual hazards were reported. This order is important in order to ensure all the direct substance hazards from a material are taken into account, since the user will be interacting directly with the material. As stated above, if direct hazard data was missing, then residual hazards were reported when applicable. Some endpoints did not have any direct or residual hazard data.

Although process chemistry information was collected such as the chemicals used in the upstream process, its function and frequency of use, the hazards associated with the process chemistry were not analyzed. This was done in order to limit the boundary of this research. The focus of this research is on hazards associated directly with materials. While process chemicals feed into materials and can therefore play a role in the safety of the materials down the line, collecting the data for the materials themselves is a complex task and a realistic boundary had to be drawn. It is important to note that including the process chemistry to the boundary of this research would provide a complete life cycle assessment of the materials, as discussed in Chapter 4.

Pharos Data Collection

In order to evaluate the hazards associated with each filament material, a hazard assessment was conducted for all the material filaments under investigation in this study. Often, material manufacturers add proprietary chemicals and additives in order to differentiate their filament from other manufacturers. Although an attempt was made to collect this information from MSDS sheets and from calling the material manufacturers, it was largely unsuccessful. Therefore, the hazard assessment for the material filaments in this study was conducted on the base material of all the filaments. The biggest drawback to this methodology is that the hazards for filaments with the same base material yet made by different material manufacturers cannot be distinguished from one another. In other words, all filaments with the same base material have the same hazards regardless of the additives added by their material manufacturer. In addition, other additives are typically used to provide different colors for the material filaments. These color additives may result in additional hazards, yet Pharos does not distinguish hazards according to the color of the material.

Appendix A.5 highlights the hazards collected for the varying base materials of the filaments analyzed. A portion of that data is shown in Figure 5.3 below. The hazard assessment was conducted on the 18 endpoints reported in Figure 4.4. The governing body or agency that reported the hazard and its severity level were also identified next to each hazard data endpoint reported, and the severity level was color coded from red indicating highest concern to green for lowest concern. Only the hazard levels were collected and not the priority levels that Pharos assigns to each hazard. As can be seeing in Figure 5.3, the material name and CAS number are reported at the top; the first column identifies the endpoint under evaluation; the second column identifies the hazard level of its corresponding endpoint; the third column lists the authoritative source that identified the hazard.



ABS
CAS No. 9003-56-9

Endpoints	**Hazard Level**	**Reported Authoritative List**
Carcinogenity	🟧 Acrylonitrile	US EPA- IRIS Carcinogns 1986 Group B1
Gene Mutation	🟨 Acrylonitrile	Japan- GHS- Category 2
Reproductive Toxicity	🟧 Acrylonitrile	Japan- GHS- Category 1B
Developmental Toxicity	▨	
Endocrine Activity	▨	
Mammalian Toxicity	🟥 Acrylonitrile	US EPA- EPCRA Extremely Hazardous Substance
Organ Toxicant	🟨 Acrylonitrile	EU- GHS- H335
Neurotoxicity	🟦 Acrylonitrile	G&L- Neurotocix Chemicals
Skin Irritation	🟧 Acrylonitrile	EU- R38
Eye Irritation	🟥 Acrylonitrile	EU- GHS- H318
Skin Sensitization	🟧 Acrylonitrile	MAK- Sensitizing Substance Sh
Respiratory Sensitization	🟨	AOEC- Asthmagens Suspected asthmagen (R)
Reactivity	🟧 Carbon Black	Japan- GHS- Category 1
Flammability	🟧 Acrylonitrile	EU- GHS- H225
Acute Aquatic Toxicity	🟧 Cuprous Chloride	EU GHS H400
Chronic Aquatic Toxicity	🟧 Cuprous Chloride	EU GHS H410
PBT	🟥 Polycyclic aromatic hydrocarbons (PAH)	OSPAR
Persistence	🟦 Acrylonitrile	EC- CEPA DSL
Bioaccumilation	🟦 Acrylonitrile	US EPA- PPT- TSCA
Terrestrial	🟧 Acrylonitrile	New Zealand- GHS 9.2A

🟥	Very High
🟧	High
🟨	Moderate
🟩	Low
⬜	Potential Concern
▨	Data not Available

Figure 5. 3 Example of the hazard data collected from Pharos for ABS [163]

Finally, as can be seen in Appendix A.5 and Figure 5.3, some hazard levels of the endpoint data contain additional chemical names. As explained above, Pharos categorizes the hazards into two groups, those associated with the substance itself and those from process chemicals and residuals, known as potential residual hazards. Thus, hazard levels that are color coded but left blank are direct substance hazards whereas hazard levels containing a chemical name indicate that the chemical contributes a residual hazard. For example, in Figure 5.3 respiratory sensitization's hazard level is moderate and left blank, signifying ABS causes respiratory sensitization. Yet, carcinogenicity endpoint is labeled as high and has "Acrylonitrile" written since the hazard is caused by the Acrylonitrile used in ABS as a monomer. If a material contained both a direct substance hazard and a residual hazard, the substance hazard was reported instead since it directly affects the material as is. If no substance hazard was reported, then residual hazards were collected instead. The biggest challenge to collecting the hazard data was the lack of data. Data gaps signify that the endpoint hazard has not been tested thoroughly enough or even at all in order to reach a conclusion on its impact. Therefore, a thorough conclusion on the safety of a material cannot be made with a missing hazard since the endpoint may or may not exist.

MSDS Data Collection

As stated in Chapter 4, material safety data sheets (MSDS), provide information on chemicals and chemical compounds and mixtures. The information required to be reported on MSDS is divided under 16 headings, summarized in Appendix A.4. Of the 16 categories, data collection under the hazard(s) identification, composition/information on ingredients, exposure controls/ personal protection, toxicological and ecological information, and regulatory information were the most relevant to the development of the tool. The information listed under these categories helped capture a complete overview of each material as discussed below. Yet, the MSDS sheets did not help simplify the complexity of material hazard data, rather it added more important information regarding to the safety of the material.

In order to develop a complete overview of each of the 36 materials under examination, each MSDS sheet from the material manufacturers were obtained [154]–[158]. Although most of them were found online, some manufacturers had to be called in order to supply this information. The first purpose of collecting these MSDS sheets was to identify the composition and additional ingredients used in the material that can provide more information on the hazards associated with that material. Unfortunately, these were often listed as proprietary. The second purpose was to gather additional data on physical and chemical properties that were sometimes applicable to the performance data properties that were collected earlier. Then the sections pertaining to hazards identification, toxicological information and ecological information on the MSDS sheet were collected and compared to the hazards reported and obtained by Pharos. In most cases, the hazards from MSDS sheets generally matched the direct material hazards reported from Pharos and sometimes even the residual hazards, yet the process chemicals that caused the residual hazards were not listed. Although more data was collected from Pharos then MSDS, it was important to cross check the hazards the MSDS sheets report as they are usually used when handling material. Yet conducting a hazard assessment by using Pharos provided a more complete picture of where these hazards are coming from. Finally, the remaining data reported on the MSDS sheets were collected for further safety information such as first aid measures, fire-fighting measures, handling and storage, exposure controls and personal protection, stability and reactivity, disposal information, and regulatory information. Exposure controls and personal protection collected from the MSDS were relevant to the development of the tool in order to integrate safety measures. Yet, most of the safety measures reported by the MSDS were addressed on a superficial level, such as using the materials in a well-ventilated space, using respiratory protection, and using appropriate gloves to prevent burns.

Regulatory Data Collection

As previously stated, empirical research from the interviews revealed regulatory compliance is required for certain products and therefore taken into consideration during the product development process. Thus, regulatory information was also collected from MSDS sheets in order to determine the material's compliance to certain applications and geographic locations. The regulatory category in the MSDS listed the specific regulation in each country that the material met. For example, it indicates if a material meets REACH requirements under the European Regulations, Toxic Substance Control Act (TSCA) under the US Federal Regulations, as well as others regulatory bodies such as US State Regulations and Canadian Regulations. It is interesting to note that under the Regulations section of the MSDS, some of the plastics were labeled under the Annex V of Regulation (EC) No. 1907/2006 (REACH) which exempts certain substances, such the additives used in the polymers in this case, from the registration and evaluation of REACH because it is deemed inappropriate or unnecessary, irrespective of the tonnage at which they are manufactured or imported [164].

In addition to the MSDS sheets, other regulatory compliances were obtained from the material manufacturer's websites. Often these were listed in very broad terms such as "medical grade approved" or "FDA approved." Yet medical grade and FDA approval have different tiers that greatly vary the regulations around them. For example, a material that is defined as medical grade should be further classified according to if the material will be touching a body from the outside, such as skin contact or if it will be inside a body such as dentures or heart valves. More data regarding the FDA tier or medical grade for the 3D printing materials were not collected although they could be found on the material manufacturer's website. Some listed the information under the Regulatory section or Other section in the MSDS sheets while other manufacturers had the information on a separate sheet labeled as "Deceleration of Compliance."

Therefore, although material compliance is often thought to be binary (either compliant or not), this section outlines some complexity to the regulatory data collection process. For example, some additives within the materials do not need to be reported. Moreover, regulations reported on MSDS specific to the food and beverage industry or the medical industry cannot be taken at face value, rather the user must search further for more specific information that may change the regulatory policy around the material.

VOC and UFP Data Collection

The last sustainability data set collected was for information on volatile organic compounds (VOCs) and ultrafine particles (UFPs). VOC's are organic compounds (compounds that contain carbon) that easily become gasses from certain solids and liquids. VOCs are widely found in household products, building materials, furniture, office equipment, printing equipment, and craft materials [165]. VOCs vary in their ability to cause health effects; some have no known effects while others are highly toxic. Moreover, the toxicity of VOCs depends on the location, level, and length of exposure [165]. In the case of 3D printing materials, multiple VOCs may be emitted from one material filament in different quantities. Moreover, each VOC emitted has its own exposure limit. VOC limits are set by The National Institute for Occupational Safety and Health (NIOSH), Occupational Safety and Health Administration (OSHA), Association Advancing Occupational and Environmental Health (ACGIH) and the EU Occupational Exposure Limits (OEL) and categorized according to the length of exposure [88]. Acute exposure refers to one hour, chronic exposure is one year, short term exposure limits (STEL) are 15-minute time weighted averages, ceiling threshold limit value (CTLV) are limits that should not be exceeded at any time, and permissible exposure limits (PEL) and recommended exposure limits (REL) are eight-hour time weighted averages (TWA) [166].

Ultra-fine particles are particles that are under 100 nanometers (or 0.1 micrometers) in diameter. They are often generated from emissions of process-related work such as motor vehicle emissions. The main exposure to UFPs is through inhalation and thus its major health hazards are related to respiratory illnesses [167]. Although UFPs are considered to be air pollution, they are not regulated. The closest regulations are set by the federal EPA [168] and state CA EPA [169] for particulate matter (PM) that is less than or equal to 10 micrometers and 2.5 micrometers. The limits are divided into two categories, a 24-hour limit and an annual arithmetic mean, averaged over 3 years [168]. Table 5.5 highlights the PM limits set by both agencies.

Table 5. 4 Particulate matter emission limits

	EPA	CA	EPA	CA
	2.5 µm		10 µm	
24 Hour	35 µg/m3	-	150 µg/m3	50 µg/m3
Annual Arithmetic Mean	12 µg/m3	12 µg/m3	-	20 µg/m3

VOCs and UFPs are emitted from 3D printing filament materials when they are heated during the printing phase. In order to collect the VOC and UFP emission data, on site air quality testing is required. The emissions from the 36 material filaments were not tested due to the lack of proper equipment to perform the tests. Rather the VOC and UFP data was collected from Azimi et al. [141]. Although other research papers also addressed UFP and VOC emissions [139], [140], Azimi et al. tested a variety of materials in their work in comparison to others. Yet, not all of the base materials related to this research work were tested in Azimi et al. study; they were limited to ABS, PLA, HIPS, nylon, laybrick, laywood, polycarbonate, PCTPE, and T-Glase [141].

Azimi et al. reported the top 10 VOC emissions from each material they tested. Yet when looking at their data, the largest contributors of VOC emissions for every material was due to the top three VOC emissions. Therefore, the top three VOC emissions for every material reported was collected for this research along with the UFP emissions for every material. After collecting this data, the hazards associated with each VOC present was examined. In order to do this, first the exposure limits for the top three VOC emissions from every material was collected from the OSHA and NIOSH. NIOSH researches and recommends the VOC exposure standards that are then reported as the required regulations from OSHA [170]. The exposure limits were compared to the actual emissions that Azimi et al. reported. In addition, the hazards associated with each VOC was also collected from OSHA rather than Pharos. There are a few reasons for this decision, the data from OSHA directly relates to workplace hazards from exposure. In this case, the study is concerned with the users printing 3D materials and exposed directly to VOCs. The hazard data could have been collected from Pharos, yet Pharos does not distinguish a styrene VOC from a styrene material, thus using Pharos would complicate this process further. Finally, UFP data was compared to the particulate matter exposure limits for 2.5 µm highlighted in Table 5.5. UFPs, although more harmful than particulate matter due to their small size, are not regulated, thus following particulate matter exposure limits was the closest regulatory compliance that they could be compared to for safety.

As can be seen, collecting VOC and UFP data is also a complex process. It does not end at testing the emissions or collecting emission data, rather the added value comes from determining what agency to follow for exposure limits, converting the emissions into data that matches those reported by the agency, comparing if the emissions are above or below their exposure limits, and what hazards are associated from their exposures.

5.5 Lessons Learned: Why material sustainability is not employed in industry

Collecting the data relating to costs, aesthetics, performance, and sustainability along with regulations for the 36 material filaments used in 3D printing revealed numerous difficulties in order to integrate material sustainability into the material decision-making process. A closer examination of the barriers is presented in this chapter.

Data Collection and Interpretation

The greatest barrier to integrating material sustainability into the material decision-making process is due to data collection. Even seemingly simple data collection such as material costs, have a layer of complexity due to possible whole sale prices or contract prices. Yet data collection of material performance properties proved to be one of the most difficult tasks. It is a messy, complex, and time consuming process. Over 20 material properties had to be collected manually for each material in this study. Moreover, multiple sources such as technical specification sheets, material manufacturing websites, material supplier websites, MSDS sheets and research papers were used in order to collect adequate material property data. Thus, in order to create a complete data base of material performance properties, it would require designers and engineers to manually obtain and enter the material information. This would be a time intensive task.

Additionally, the data collection is a messy process. As stated earlier, using multiple sources to collect material information results in inconsistencies in property terminology, reported measurement units, and property testing methodologies. Reported testing methodologies for properties ranged from ISO and ASTM standards to custom methods that were not explained and often missing.

Sustainability data collection was just as complex. Eighteen human health and environmental hazard endpoints were collected per material in order to understand the sustainability of the material. This too required obtaining data from multiple databases such as Pharos and MSDS sheets, and even research papers for air quality emission data.

Hazard data collection adds another layer of complexity; understanding the difference between hazard and risk (discussed in Chapter 4). Although risk studies the likelihood of a hazard to cause harm, it is modeled based on scientific assumptions and hard to quantify in all working conditions. Conditions vary from the route of exposure such as ingestion or dermal contact, intensity of exposure, duration and frequency. Thus, this study limited the data collection to the hazards associated with materials.

In addition, when using Pharos, hazard data is reported as both a hazard level and as a Pharos priority level. A user must understand the difference and know what data they are collecting. Moreover, of the hazards that are reported by Pharos, they can be direct substance hazards and/or residual hazards due to the manufacturing process chemistry of the material. Therefore, a user must set a system boundary when collecting material hazard data in order to determine what hazards are relevant to their analysis. If the system boundaries include the upstream material manufacturing phase, then engineers and designers must understand the manufacturing process when considering residual hazards in order to evaluate the magnitude of the hazard. This represents another challenge to hazard data collection and interpretation.

Engineers and designers are not hazard experts. Thus, of the hazard data collected, prioritizing each hazard endpoint presents another challenge. When collecting 18 hazard endpoints with varying levels of harm, it is difficult to prioritize for example carcinogenicity over neurotoxicity or developmental toxicity or persistence and bioaccumulation. Ideally, the engineers and designers would have to determine how the material will be managed and its potential for exposure in order to prioritize the hazards considered to be harmful. Yet, relying on personal interpretation on how to prioritize these endpoints will result in inconsistencies during material decisions.

Finally, air quality properties such as the emissions of VOCs and UFPs are typically manually collected and tested. Yet, different printing and testing environments such as the size and shape of the part printed, if the printer is in an enclosure, the size of the room, and the air exchange rate within the room will also result in varying outcomes. A user should be aware of these discrepancies if they are collecting information from multiple sources instead of conducting their own emission tests.

Missing and incomplete data

Hazard data is often missing and incomplete [109], [171]. This represents the largest barrier to collecting and understanding hazard data. Incomplete data does not signify that a hazard is not present, it simply means there is not enough scientific evidence in order to evaluate the hazard [109], [171]. Thus, a missing endpoint could potentially be harmless or extremely harmful. This uncertainty in the data represents a challenge; how are engineers and designers expected to make safe and sustainable material choices with inadequate data.

Some frameworks and tools have tried to approach this problem (discussed in Chapter 4) yet there is still no right answer and methodologies on how to assess data gaps vary from person to person. As guided by frameworks, some choose to ignore these data gaps and base their decisions on what data is available while others choose to assume the worst-case scenario- if the data is not there, then it is treated as extremely hazardous. Yet either extreme assumption may result in a wrong decision. Other proposed options are to use a weighted scheme for the different endpoints and “loose” points for missing data, yet these weighting schemes are subject to interpretation. Different hazards may have different weighting schemes according to the person conducting the analysis.

Viewing Hazard Impacts Through a Life Cycle Perspective

Hazards can be viewed through a life cycle perspective. This presents another difficulty and uncertainty; where should engineers and designers take into account the multiple material impacts based on a life cycle perspective? If a company sets their system boundary when considering hazard data collection for material sustainability analysis, then engineers have a clear guidance. Yet if a company does not set the boundary, then the impacts under consideration will differ according to personal values.

Figure 5.4 highlights the life cycle stages and their associated material impacts. As can be seen, the life cycle of the material is divided into five stages; raw material extraction, material processing, product manufacturing, product use, and end of life. Generally, raw material extraction and material processing hazards focus more on ecotoxicity, resource depletion, and global warming potential. If material processing is considered in the system boundary, then residual hazard data should be collected. The product manufacturing stage is when the materials under consideration are used in order to create a product. The product manufacturing and product use phase place an emphasis on human toxicity and physical hazards due to the materials in use. Depending on the manufacturing process of the product, the direct substance and/or the residual hazards of the materials may need to be included in a hazard assessment. Finally, the last stage of the life cycle is end of life. This stage tends to focus on ecotoxicity hazards although human health hazards may play a role. It is important to realize in each life cycle stage, the impacts are not mutually exclusive, both human health and environmental hazards are present yet Figure 5.4 highlights the most common hazards in each stage. These are the different impacts in every life cycle stage that a designer or engineer would have to collect data, analyze and interpret in order to understand the complete life cycle impact of the materials they are choosing.

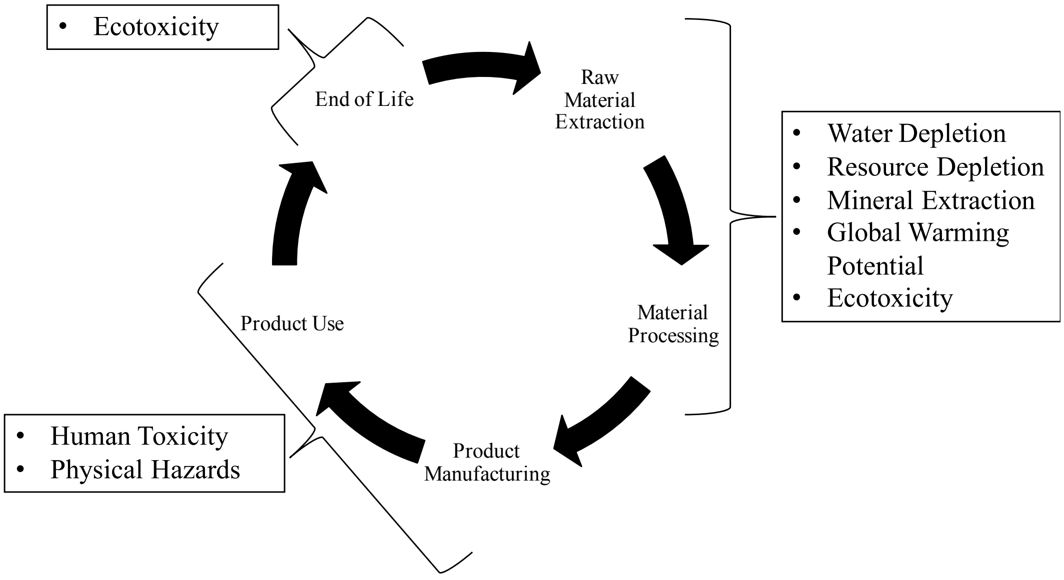
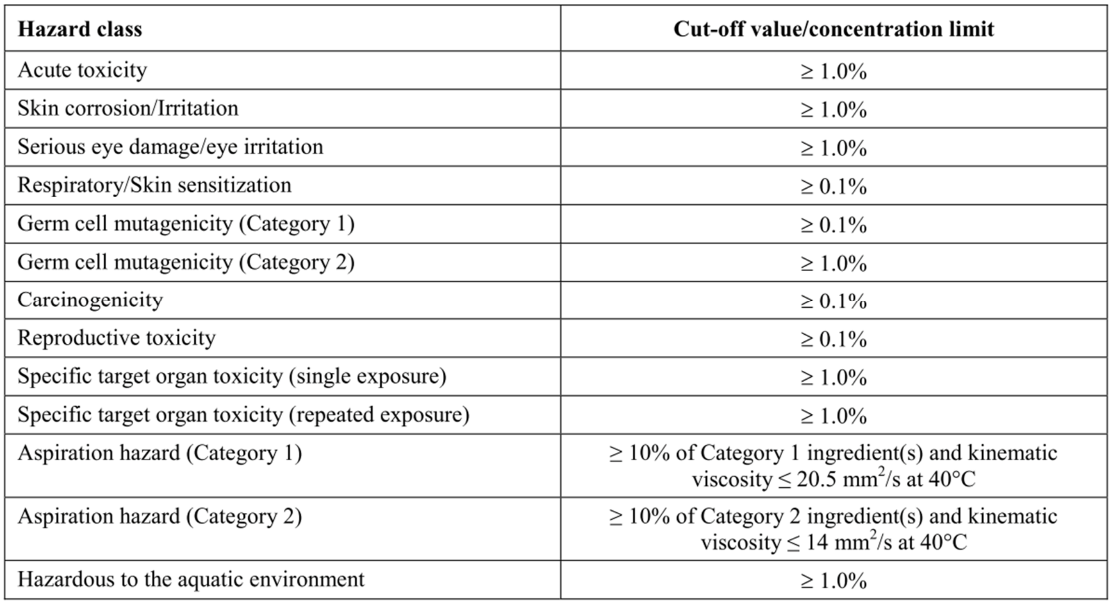


Figure 5. 4 Material impact hazards according to life cycle stage

Understanding Regulations

Finally, the last barrier to integrating material sustainability is understanding regulations. The first complexity to this is realizing that some agencies set different exposure limits. This was clearly visible when collecting VOC and UFP data. VOC limits are set by OSHA, NIOSH, ACGIH, and EU OEL [88]. Moreover, they are categorized by length of exposure such as one hour, one year, short term 15-minute time weighted averages, ceiling threshold limit values that are not to be exceeded at any time, and permissible exposure limits (PEL) and recommended exposure limits (REL) for eight-hour time weighted averages (TWA) [166]. Collecting and understanding this data, how it relates to the length of exposure at a facility, and how the exposure times are calculated, as well as what agency to follow, adds another complexity to understanding material sustainability.

Moreover, although MSDS sheets are targeted towards people who are handling chemicals and materials in an occupational setting and provide technical and scientific information, some of their guidelines are often generic. These sheets are required to list hazardous chemicals in a product that are found in quantities over the cut-off values reported in Figure 5.5 [153]. Yet, the amount of the hazardous chemical in the material is not required to be reported. In addition, proprietary or trade secret chemicals can be claimed and added in the MSDS as “proprietary.” Ecological information, disposal considerations, transport information and regulatory information must be consistent with the UN-GHS yet are not regulated by OSHA, rather they are handled by other governing agencies. Exposure controls and personal protection are usually basic and recommend the use of suitable ventilation and respiratory protection to avoid threshold limits, gloves for heat protection and chemical spills, and safety glasses. Finally, many polymers in the MSDS may fall under the Annex V Regulation (EC) 1907/2006 (REACH) stating that additives in polymers are exempted from registration, evaluation and downstream user provisions thus limiting the regulations specific for the product [164].



Hazard class	**Cut-off value/concentration limit**
Acute toxicity	≥ 1.0%
Skin corrosion/Irritation	≥ 1.0%
Serious eye damage/eye irritation	≥ 1.0%
Respiratory/Skin sensitization	≥ 0.1%
Germ cell mutagenicity (Category 1)	≥ 0.1%
Germ cell mutagenicity (Category 2)	≥ 1.0%
Carcinogenicity	≥ 0.1%
Reproductive toxicity	≥ 0.1%
Specific target organ toxicity (single exposure)	≥ 1.0%
Specific target organ toxicity (repeated exposure)	≥ 1.0%
Aspiration hazard (Category 1)	≥ 10% of Category 1 ingredient(s) and kinematic viscosity ≤ 20.5 mm^2/s at 40°C
Aspiration hazard (Category 2)	≥ 10% of Category 2 ingredient(s) and kinematic viscosity ≤ 14 mm^2/s at 40°C
Hazardous to the aquatic environment	≥ 1.0%

Figure 5. 5 Cut off values/concentration limits for each health and environmental hazard class, from [172]

Understanding the barriers presented above will help start a conversation in order to address material sustainability and integrate it into the decision-making process in industry. Currently, data is lacking and limited, and of the data available, engineers and designers would have to be hazard experts in order to understand it. Moreover, they would have to spend the time collecting and interpreting the data as they see fit. This process is not scalable and presents personal bias into the sustainability assessment.

Chapter 6

Creating the Material Decision-Making Tool

One of the goals of this research was to create a tool that maps the trade-offs to be made among costs, performance, aesthetics and material sustainability in order to facilitate more sustainable materials choices. Yet, given the barriers to integrating sustainability into the material-decision making process, discussed in Chapter 5, the scope of the decision-making tool was slightly altered. Creating this tool provides a means to start the conversation on how to address more sustainable material decision making in the design process. This tool shows how difficult it is to capture the relevant material data and create a platform that integrates into the user workflow and influences decision making. This is the first step taken in order to create such a platform. Creating the tool in essence created a set of specifications for creating a more robust materials information and analysis platform in the longer run.

Figure 6.1 outlines the relationship between user inputs, process, outputs and data to inform material selection, discussed in Chapter 5. In this chapter, the focus is on the *process* of converting user inputs to outputs using data collected from Chapter 5, and the *outputs* from the process in order to map trade-offs between materials. The user inputs are captured in the user interface created for the tool, the tool's code programmed in Excel is the process used for this research project, and the outputs are visualizations from the tool, to be discussed below.

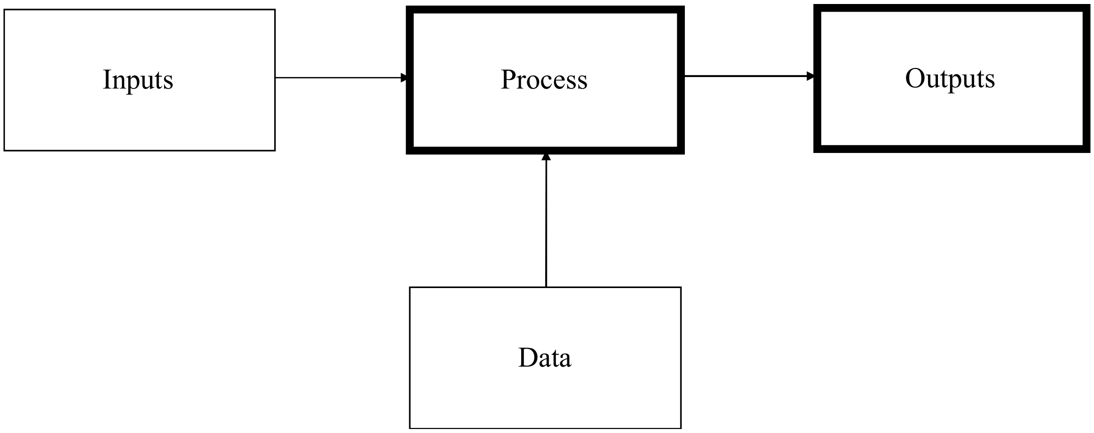


Figure 6. 1 Relationship between user inputs, process, outputs and data information to inform material selection

6.1 Boundaries of the Tool

Achieving sustainability is a complex problem. Tackling this complexity remains intractable, particularly when looking across an entire life cycle; as shown in Chapter 5, much of the required data is missing or hard to extract. Yet, to make good materials choices we must find ways to create appropriately comprehensive models. The model developed in this chapter reduces complexity by focusing on the product manufacturing phase of the LCA, allowing the model to aim to represent the full complexity of that stage. That allows us to better understand what is needed to develop usable models.

As discussed in Chapter 5, in each of the life cycle stages of materials (raw material extraction, material processing, product manufacturing, product use, end of life), different human health and environmental hazard impacts play a role. Defining the boundaries of the system helps enhance the relevant material data to be collected. Chapter 5 also highlighted that hazard data was often incomplete. The lack of data prevents any concrete trade-offs to be made and instead introduces assumptions and conjectures into the decision-making process. Moreover, some hazard data was related to substance hazards while others were related to manufacturing process hazards. Therefore, limiting the scope of the tool to the printing hazards phase, which falls under the product manufacturing life cycle stage, defines the sustainability data needed to be collected: VOC and UFPS emissions and direct material substance hazards. Yet, the materials being used for 3D printing do not have any direct material handling hazards, thus the sustainability of the materials was limited to the VOCs and UFPs released during printing.

6.2 Writing the Code

The tool was created in Microsoft Excel using Visual Basic for Application (VBA) to write the code. VBA is a Microsoft programming language that is included in the Microsoft Office package, and can be used to automate some aspects of Excel. Excel was used because it is highly accessible to users.

To start, the data collected for all 36 printing filament materials (described in Chapter 5) was entered into the worksheets. The material description, performance properties, printing guidelines, aesthetics, costs and regulations were entered on one worksheet named “Performance”. Therefore, “Performance” included information regarding: material, price, printing temperatures, melting temperatures, Tg glass transition temperatures, print bed temperature, printing speeds, density, ultimate tensile strength, yield tensile strength, young’s modulus, ultimate elongation, FDA compliance, UL flammability compliance, REACH compliance, RoHS compliance, available colors, and adjectives used to describe each material. All of these data were collected per the description in Chapter 5.

Properties that had ranges, such as printing temperatures, were divided into two columns; the first signified the minimum printing temperature and the second the maximum printing temperature. Each regulatory compliance requirement (e.g., FDA, REACH, RoHS) was listed in its own column and if a material met that regulation then a “Yes” would be placed in that column. Finally, for cells that contained more than one entry, such as cells that were under the Color or Description columns, the data in each cell was separated by commas. For example, if a material was available in white, black and red, then under the column for Color, the cell for the material would be listed as: white, black, red. The same was done for description, the adjectives for each material were separated by commas: e.g., flexible, bendable.

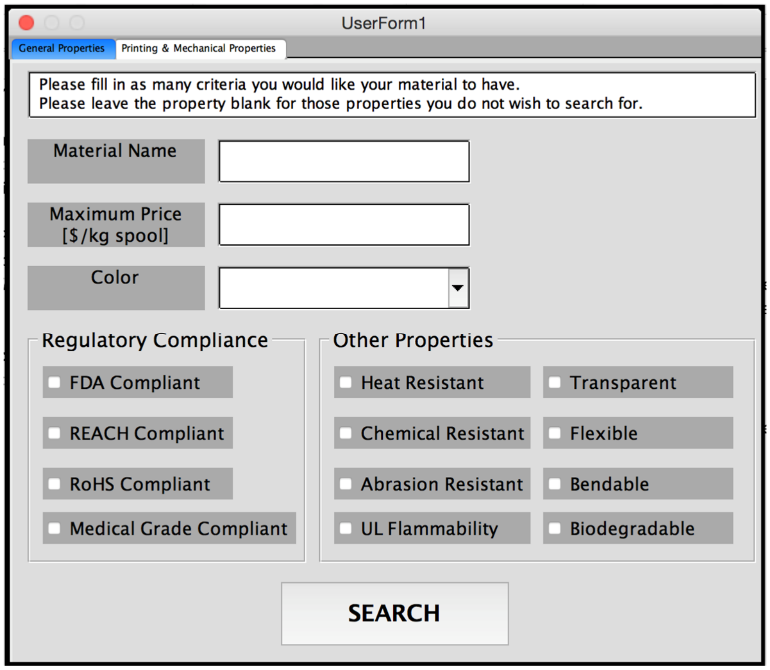
On another worksheet named "Sustainability" in the same Excel file, the data collected on the material sustainability was entered. The data included for each material were: material, base material, known composition, VOC emissions from printing, UFP emissions from printing, major VOC contributor and its associated hazards, VOC recommended exposure limits, MSDS warnings, direct substance hazard warnings, personal safety and exposure controls.

The data on the "Performance" and "Sustainability" worksheets comprise the full set of data on cost, performance, aesthetics and sustainability associated with each of the filaments. Per the discussion in Chapter 5, there are many holes and inconsistencies in this data that need to be filled (e.g., through standards improvement), this data changes regularly and thus the tool would require a means of being regularly updated, and the representation of the data is complicated by the mixed qualitative and quantitative nature of the data. The data entry process used to build this tool was highly labor intensive and required considerable judgment to process the disparate data sources. Such an approach is not sustainable if such a tool is to be broadly circulated and used.

After the data entry, the first step to make this tool was to create the Userform. The Userform is the tool interface that the user will see when the tool is launched. It was created from the VBA editor, and a Multipage option was chosen in order to create two pages on the tool interface. The first was labeled as "General Properties" while the second was labeled as "Printing and Mechanical Properties." Then on each page, more of the controls were added and labeled as necessary, as discussed below. The search criteria on these two pages were created based on the user interview data: costs, performance, aesthetics, and regulatory compliancy. Yet, the Userform purposely separated the data into two pages in order to simplify the interface of the tool and facilitate its use. The first page, "General Properties," aimed to address the high-level material needs of users such as color and compliance while the second page "Printing and Mechanical Properties" aimed to address the specific material needs for a product such as its tensile strength, and the specific printer specifications that a user may have. The tool interface was iterated with users to assure it was easy to use and the search criteria met their material specification needs.

On the General Properties page, labels were created for users to input/select Material Name, Maximum Price, and Color. These boxes allow the user to search for a material based on the type or name of a material they input, the color they select, and/or the maximum price of a material they are willing to pay. Below those, two frames were outlined, one labeled as "Regulatory Compliance" and the other as "Other Properties." Under Regulatory Compliance, a check box was placed for each: FDA Compliant, REACH Compliant, RoHS Compliant, Medical Grade Compliant. This allows the user to select which of the applicable regulatory compliance standards their material needs to meet. The Other Properties frame consisted of check boxes for Heat Resistant, Chemical Resistant, Abrasion Resistant, UL Flammability, Transparent, Flexible, Bendable, and Biodegradable. This also allows the user to select which other properties they would like their material to have.

At the top to the same page, a text box was placed with user instructions and finally at the bottom of the same page, a Command Button labeled as "SEARCH" was placed. Figure 6.2 displays how the General Properties page looks in the tool.



Please fill in as many criteria you would like your material to have.
Please leave the property blank for those properties you do not wish to search for.

Figure 6. 2 General Properties page of the Userform

On the Printing and Mechanical Properties page, 11 label boxes included: Printing Temperature, Melting Temperature, Tg Glass Transition Temperature, Melt Index, Printing Bed Temperature, Printing Speed, Density, Ultimate Tensile Strength, Yield Tensile Strength, Young's Modulus, and Ultimate Elongation. These boxes allow the user to input the material properties their material needs to meet in their product as well as printing properties their printer specifies. Figure 6.3 displays the Printing and Mechanical Properties page of the Userform.

The inputs and search criteria on both pages were selected based on the user interviews and surveys. As stated, costs, aesthetics and performance are always a concern when selecting materials, and depending on the application of the product, certain regulatory requirements must be met. Thus, this tool aimed to address these concerns. The tool was iterated with users in order to make sure they were able to specify their needs. Costs, aesthetics and regulatory requirements were placed on the first page of the tool along with other properties in order to display the high-level material requirements a user needs. The regulatory compliance requirements were chosen according to the ones most frequently cited from the interviews. The mechanical properties and printing guidelines were also chosen based on the most frequently cited requirements when choosing a material and when choosing a material for 3D printing.

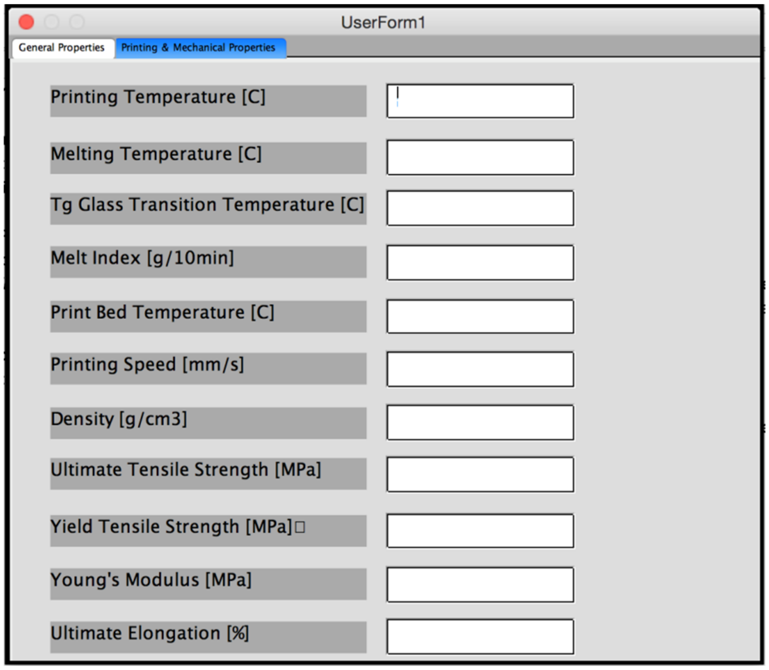


Figure 6. 3 Printing and mechanical properties page of the Userform

Now that the user interface was complete to allow users to enter their material search inputs, the next step was to write the code, or process as describe in Figure 6.1, to accompany it.

First, on a separate worksheet within the same Excel file, renamed “User Instructions”, instructions were written for a user on how to launch and use the tool (described in the section below) and a button labeled as “Launch Material Search Tool” was placed. This button launches the Userform that was created and described above.

The first line of code was related to the “Launch Material Search Tool” button. It stated that when the button is pressed, launch the Userform and create a dropdown menu for the color box in the Userform with the following options: Black, White, Natural, Red, Blue, Green, Orange, Yellow, Purple, Brown, Silver, Gold, Pink. This basically allows the user to search a material by the colors listed in the dropdown menu.

Before continuing to write the code, four extra blank Excel sheets were added into the Excel file. Two were not renamed and kept as “Sheet 2” and “Sheet 3” whereas the other two were renamed to “Variables 1” and Variables 2.” Finally, one more Excel sheet was added to the file and renamed as “Hidden.” In the Hidden worksheet, numbers were placed in the first row from number 1 to 22. Each number represented a column number. Therefore, underneath each number, the heading of each of the columns in the database of information located on “Performance”, was matched and written accordingly. Each one of the headings represents one of the properties that a user can search for in the Userform. Moreover, since properties that had ranges were divided into two columns to represent their maximum and minimum, each property with a range was written twice to represent both columns. Finally, under each number and property combination, either an “S,” “LT,” or “GT” was placed, described below. Figure 6.4 provides a small sample of how this sheet of information looked.

- S -signifies the property is a string of characters
- LT –signifies that the property is a number, and the code should search for a number equal or lower than
- GT –signifies that the property is a number, and the code should search for a number equal or greater than

1	2	3	4	5	6	7	8
Material	Price	Printing Temperature [C]	Printing Temperature [C]	Melting Temperature [C]	Tg Glass Transition Temperature [C]	Print Bed Temperature [C]	Print Bed Temperature [C]
S	LT	LT	GT	LT	LT	LT	GT

Figure 6. 4 Example of data written in the “Hidden” worksheet

The rest of the code addressed how to search for what the user enters in the tool interface. First, the material property and description data for all the 36 materials that were entered in Performance, was copied into Variables 1. Then, for every data point entered by the user into the tool interface and for every check box that was clicked, that data was stored in Sheet 2. The user input would go into the first column in Sheet 2, while the given descriptor label of the user’s input (e.g., Color, Young’s Modulus, FDA) was entered into the second column.

A function was then written in order to compare what the user entered to the information that was entered in the Hidden worksheet. The function would compare the descriptor label (column 2 in Sheet 2) to row 2 in the Hidden worksheet, if they matched, then an array was created to store information. The information in the array consisted of the column number and the accompanying descriptor: S, LT or GT. Another function was then written that would start the material filtering process according to the user’s input. It would go to Variables 1, where all the material data was entered, and go to the column that matched the first column number that was stored in the array. Then according to the S, LT, or GT descriptor, it would compare each of the material information in that column to what the user entered. If that column was labeled with an LT, then it would look for materials that had a number lower than what the user entered. If the column was labeled with a GT, then it would look for materials with a number greater than what the user entered. Finally, if the column had an S, then it would search for a specific word as a string. If there were multiple words (such as in the case for colors and description), then it would search through the whole cell, using a comma as a separator. This means, if the first letter did not match during the search, it would find the next comma and start the search again until no more commas existed in the cell. For every match, a “YES” would be stored for that material, meaning the material matched the user’s first input. Then, using the If function, if a material had “YES” stored, then all that material’s information would be copied from Variables 1 onto the Variables 2 sheet. Variables 1 sheet was then cleared and Variables 2 became the active sheet with a filtered list of materials based on the first criteria entered. Now, the next criteria the user entered, otherwise known as the next column that was stored in the array was searched through Variables 2. All the materials that met the user’s requirement and given a YES were then copied into Variables 1 again, making it the current active sheet, and Variables 2 was cleared. This process continued back and forth until it went through all the user’s inputs. A simplified flow diagram of the code described here can be seen in Figure 6.5.

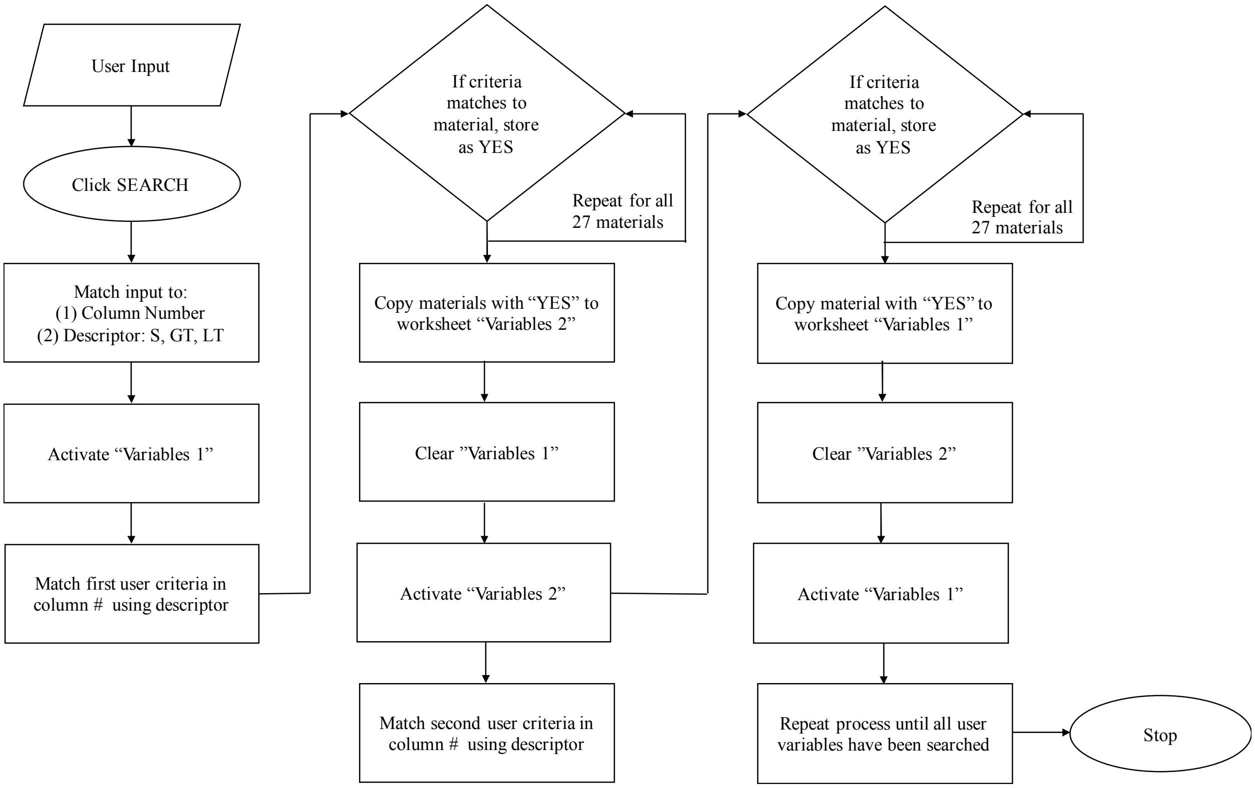


Figure 6. 5 Simplified flowsheet of how code searches through materials based on user input

After the code ran through all the 36 material options, the remaining materials in the active sheet were the materials that matched all the search criteria that the user entered. Thus, the code was written to copy the remaining materials and all their properties from the active sheet onto a new sheet called "Performance Results." Moreover, for properties that had ranges, instead of having two separate minimum and maximum columns for one property, the code joined the ranges into one column, adding a "-" between the values. For example, a printing temperature for a given material was written under the Printing Temperature column as "225-235." Properties with ranges that did not have any data available were also altered in order to output "Data Unavailable" in the cell instead of "Data Unavailable – Data Unavailable."

The material names listed in the Performance Results tab were then copied to a new sheet called "Sustainability Results." The code would then go through an If loop in order to obtain the sustainability data of the resulting materials that meet the users search criteria. The code was written to take the first material name on the Sustainability Results page and match it to itself in the Sustainability database excel sheet. When they would match, the whole row of data from the Sustainability sheet would be copied into the material row under the Sustainability Results page. Then the code would go on to the next material on that page until all the information was obtained for the resulting materials and placed in the "Sustainability Results" page.

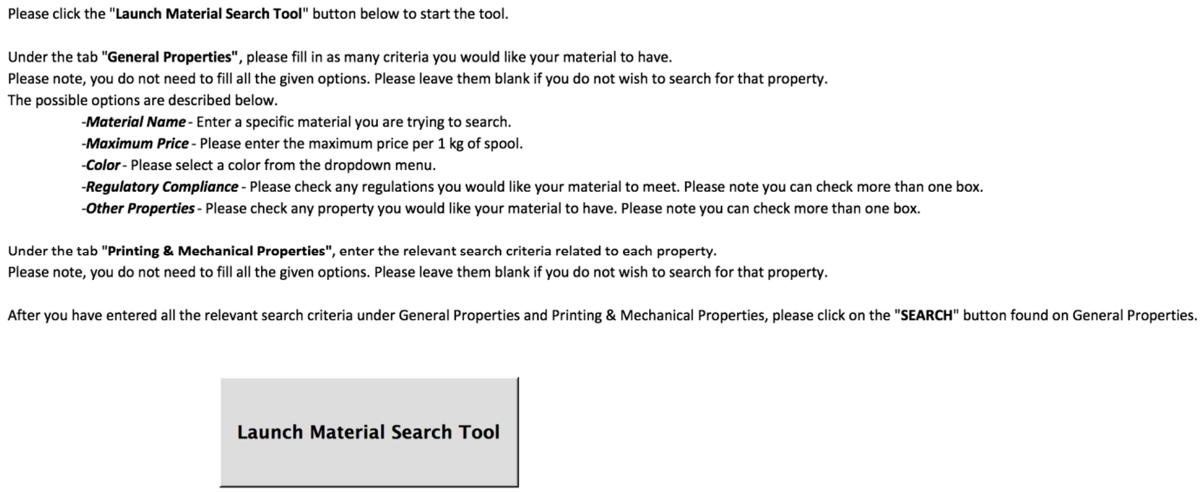
Finally, all the extra sheets used for the code were hidden from the user. So, the Performance, Sheet 2, Sheet 3, Variables 1, Variables 2, Sustainability, and Hidden sheets would not be seen before, during and after a user was using the tool. Moreover, in order for an older search to not interfere with any new search criteria, a clear contents function was added before the code was to run every time a user clicked on “SEARCH.” This cleared the data from Sheet 2, Sheet 3, Variables 1, Variables 2, Sustainability Results, and Performance Results. The VBA code can be found in Appendix A.6.

In addition to the VBA code, a separate excel sheet was added and renamed to Bar Graph. In this sheet, the graph would take the material results from the Performance Results page and plot them against their price and mechanical property of choice. The price and mechanical property are on separate y-axis. The graph updates and changes the materials automatically as the Performance Results material page updates after every search.

After the search was complete, a message box would appear for the user stating “Search Complete.” The user would then be left with five tabs: User Instructions, Performance Results, Sustainability Results, Bar Char, and Sources. These will be discussed further in the next section.

6.3 Using the Tool

The tool was constructed with considerable input from users to ensure both ease of use and fit with existing materials selection processes. When opening the excel spreadsheet, the first page that opens is a list of instructions on how to use the tool, as can be seen in Figure 6.6. It explains that the first step is to launch the tool. Once launched, there are two search tabs. The first tab is the “General Properties” tab as can be seen in Figure 6.7. In there, the user can enter the specific material they are looking for such as ABS or PLA, choose the maximum price they are willing to pay per 1kg of the material spool, select the color they want from the dropdown menu, and check any other properties or regulatory compliance they would like the material to have. As stated above, the search criteria on the General Properties page aimed to address the high-level items and needs that designers and engineers are thinking about during the material selection for the product development stage.



Please click the "**Launch Material Search Tool**" button below to start the tool.

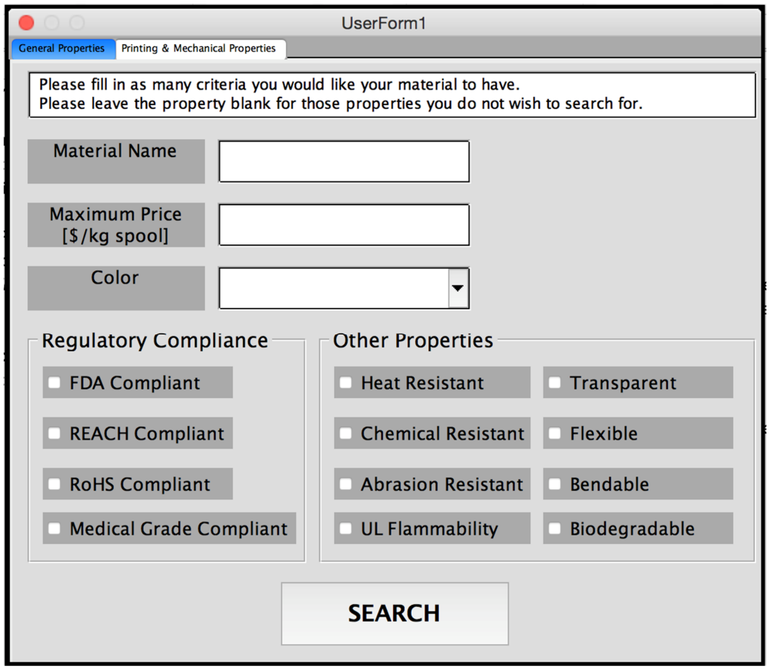
Under the tab "**General Properties**", please fill in as many criteria you would like your material to have.
Please note, you do not need to fill all the given options. Please leave them blank if you do not wish to search for that property.
The possible options are described below.

-***Material Name*** - Enter a specific material you are trying to search.
-***Maximum Price*** - Please enter the maximum price per 1 kg of spool.
-***Color*** - Please select a color from the dropdown menu.
-***Regulatory Compliance*** - Please check any regulations you would like your material to meet. Please note you can check more than one box.
-***Other Properties*** - Please check any property you would like your material to have. Please note you can check more than one box.

Under the tab "**Printing & Mechanical Properties**", enter the relevant search criteria related to each property.
Please note, you do not need to fill all the given options. Please leave them blank if you do not wish to search for that property.

After you have entered all the relevant search criteria under General Properties and Printing & Mechanical Properties, please click on the "**SEARCH**" button found on General Properties.

Figure 6. 6 Instructions on how to use the tool and material launch button



Please fill in as many criteria you would like your material to have.
Please leave the property blank for those properties you do not wish to search for.

Figure 6. 7 General Properties tab on search tool

The second tab in the search tool is the “Printing & Mechanical Properties” tab, as can be seen in Figure 6.8. On this page, the user can enter the maximum printing temperature, melting temperature, Tg glass transition temperature, and/or melt index of the material needed. Moreover, they can specify the maximum print bed temperature and printing speed of the 3D printer that will be used. Finally, they can also enter the desired mechanical properties of the material such as density, ultimate and yield tensile strength, Young’s Modulus and ultimate elongation. Again, the second page of the tool aimed to address the specific mechanical property requirements for the material needed in a product and the printing property requirements for the printer in use.

One key detail highlighted in the instructions is that not all fields are required to be filled in the tool. If a user does not need to constrain a certain property or does not need to search for it, then they can leave the option blank or unchecked. This was done in order to maintain flexibility within the tool. The search criteria in the tool were chosen according to the most frequently cited needs from the user interviews and surveys. Yet not all criteria included were required for all the users. Therefore, maintaining this flexibility allows multiple users with different criteria to use the tool. Once the search criteria are filled, the user needs to go back to the “General Properties” tab and click on the “SEARCH” button.

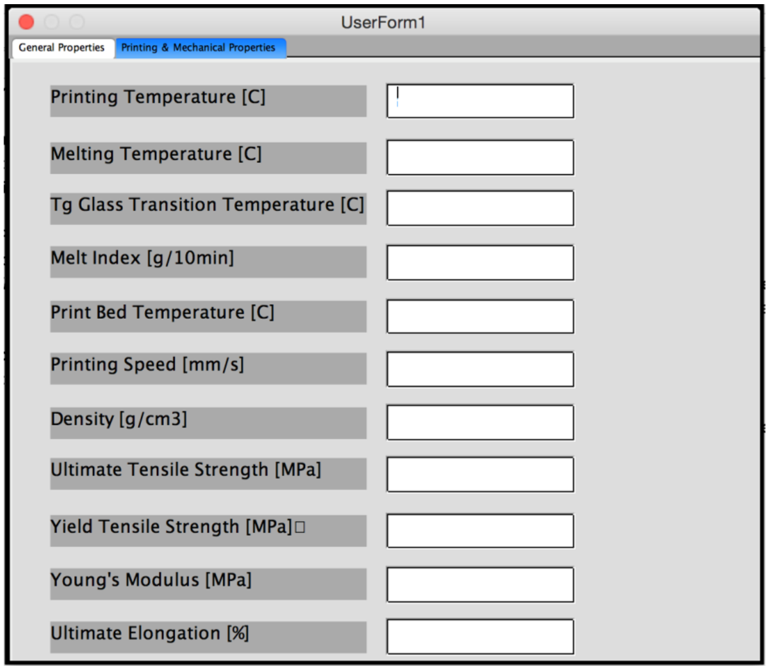
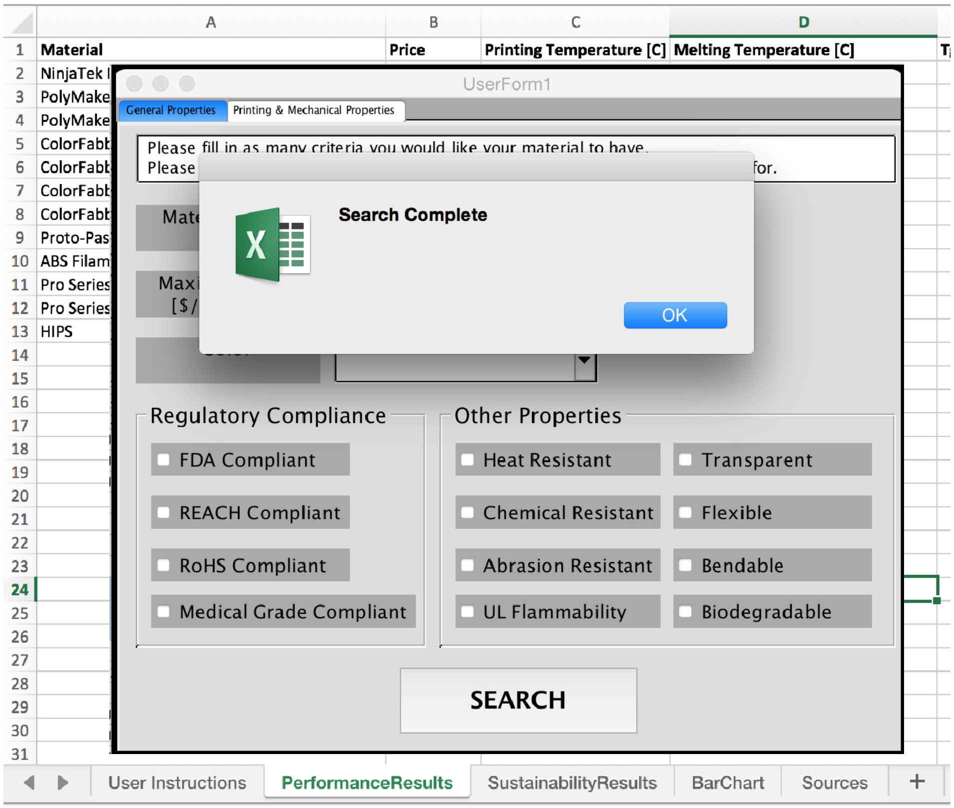


Figure 6. 8 Printing and Mechanical Properties tab on search tool

Once the user starts the search, a window will pop up stating “Search Complete.” Figure 6.9 shows the output display once the tool completed its search.



	A	B	C	D
1	Material	Price	Printing Temperature [C]	Melting Temperature [C]
2	NinjaTek I			
3	PolyMake			
4	PolyMake			
5	ColorFabb			
6	ColorFabb			
7	ColorFabb			
8	ColorFabb			
9	Proto-Pas			
10	ABS Filam			
11	Pro Series			
12	Pro Series			
13	HIPS			

Please fill in as many criteria you would like your material to have.

Search Complete

Figure 6. 9 Display of tool once search is complete

The tool would have searched all the materials in the database that meet the user's requirements and returns the material options. The user will then have 4 tabs of information to choose from on the excel window. The first tab is labeled "Performance Results." In this tab, the costs, printing guidelines, mechanical properties, description, aesthetics, and regulatory compliance of the returned materials are displayed in a table format.

The second tab is labeled "Sustainability Results." This tab contains information relating to the base material, the VOC and UFP emissions, major VOC contributors and their associated hazards and recommended exposure limits, substance hazard data, and other comments and safety measures indicated from the MSDS sheets. This information is also presented in a table format.

The third tab is labeled as "Bar Chart." This tab contains a bar graph that plots some of the search information. A number of different representations of the data were tested with the users to represent the output data. The parameters the users entered were the ones they wanted to see on the graph. Therefore, the x-axis on the output bar graph displays all material options that meet the user requirements, the first y-axis plots the price of the material and the second y-axis plots one or more of the mechanical properties that was searched for in the search tool box, if entered. The bar graph clearly represented the trade-offs to be made by material according to price and mechanical properties of interest, given the other search criteria. Qualitative data points that a user may have entered on the search tool (such as a color or regulatory compliance) were not shown on the bar graph, yet the materials plotted in the graph met those criteria. The output clearly addressed the cited needs of the users.

As stated in the beginning of this chapter, the aim of this tool was to capture the relevant material data, which it did, and also present users with trade-offs to be made among costs, performance, aesthetics and material sustainability. The bar graph clearly represented the trade-offs to be made by material according to price and mechanical properties of interest, yet not by sustainability. Given all the VOC, UFP and substance hazard data of each material, it was difficult to plot all the information since some data were qualitative and others quantitative. The "Sustainability Results" tab was present in order to allow the user to review all the sustainability data and make an impartial decision. As discussed previously, a ranking scheme of the materials based on the sustainability results was avoided since it loses a lot of relevant information. Moreover, not all the endpoint hazard data between the materials are consistent, making it difficult to prioritize the hazards. Yet in order to integrate a platform into the user workflow that maps all the tradeoffs to be made including sustainability data, it was important to address a visual representation of the sustainability data. This is discussed more thoroughly below, in Section 6.5 of this Chapter.

Finally, the last tab labeled as "Sources" indicates what sources were used to collect the material data. The "User Instructions" tab is also still available if the user would like to relaunch the material search tool.

The complete visualizations of the data in each tab for every material can be found in Appendix A.6. This also reflects the data that were collected for every material described in Chapter 5.

6.4 Testing the Tool and Iteration

After the tool was completed, it was tested individually by ten users. Four of the users are experts in material hazards and sustainability, two are experts in creating tools that enable people and companies make better decisions, and the other four are experts in 3D printing and materials although all are familiar with all three dimensions of the problem.

When testing the tool, the users were given the interface and no instructions besides the ones available on the homepage in order to determine its ease of use and clarity. Moreover, information on the number of data points a user would like to see and other recommendations or suggestions the users had on the tool were collected during and after they had an opportunity to interact with it.

Overall, the ease of interacting with the tool interface was positive. The users were able understand and navigate between the search tabs. A few users recommended adding the word “Maximum” or “Minimum” in front of the search properties under the “Printing & Mechanical Properties” tab in order to clarify what criteria the search will look for in the materials. Other suggestions included adding degrees of biodegradability and separating FDA compliance into medical and/or food compliance in the search tool and adding definitions and limits associated with the check-boxes on the “General Properties” tab. Unfortunately, the adjectives on the “General Properties” list – bendable, flexible, heat resistant, chemical resistant – are the adjectives used on the material supplier’s website to describe a material. At present, there are no further descriptions or quantification of those adjective; this is another place where standards bodies might have a role to play in enticing materials producers to provide clearer descriptions of the materials they make.

More comments and suggestions were given for the results page and display. Recommendations included adding a definition for “Data Unavailable” when listed under material properties, linking the sources for the data displayed on the results page to the separate sources tab, clarifying the bounds of the analysis, adding information from the Plastics Scorecard (discussed in Chapter 4), and adding more tangible sustainability metrics for the materials such as their water and carbon footprint.

All of these suggestions were accommodated in the final tool design, except for the inclusion of water and carbon footprint data. Although these metrics are interesting, inclusion of these data will require a more complex model that spans the entire cradle-to-grave cycle, and a credible source from which to capture the needed data. Those were outside the scope of this work, but should be considered in future iterations.

Recommendations from the hazard and material experts included not separating the performance and sustainability tabs, rather including all the data as performance data to give the hazards equal weight and attention or call the sustainability tab “Health Rating” to emphasize its health impacts. One user recommended color coding the range of concern associated with each material, without ranking them. The user suggested keeping all the hazard details in the background if the user of the tool wanted to see it and add restrictions and safety recommendations. Moreover, this user recommended making the tool modular in order to accept plug-ins, this way as data becomes available according to region, standards and regulations, internal industry or company policy or even if more information is released by a material supplier, one can simply add them in.

Another hazard expert recommended including the residual hazards associated with the materials being used since monomers still exist during and after manufacturing that users should be aware of. This will also help users be aware of the hazards associated with their waste. Other suggestions included providing explanations of the hazards and why they are important, what data gaps mean with regards to a hazard, and how to deal with exposure to these hazards.

All the hazard experts stressed defining the criteria and impacts under investigation over the life cycle of the material, stating the risks associated to exposure, and recommending safety tips or exposure controls. As most of the MSDS sheets state the same exposure controls, one user recommended adding a general safety disclaimer that includes the manufacturer and MSDS recommendations. Moreover, when looking at the life cycle of the material, one user stressed not all the criteria are as important depending on the stage; direct substance hazards and VOC and UFP emissions are most important during the use phase of the material.

In summary, a future tool should include the following:

- Cost, aesthetics, mechanical properties, printing guidelines, and regulatory compliance data of materials
- Carbon and water footprint of materials
- Direct and residual material hazard data
- Life cycle stage and associated impacts under investigation
- Exposure and safety controls
- Explanation of hazards, exposure, risk, and data gaps
- Degree of biodegradability, FDA compliance and medical compliance
- Definitions and limits or quantification associated with the adjectives used to describe materials
- Modularity in order to accept plug-ins into the tool as material information or regulatory data is released

The tool created currently has the available cost, aesthetics, mechanical properties, printing guidelines and regulatory compliancy data of the materials under investigation for this study. Moreover, it included the product manufacturing life cycle stage and its associated impacts, direct material hazard data available, exposure and safety controls, as well as the explanations of hazards, exposure, risk and data gaps. Yet, the remaining data that was recommended by the user interviews such as carbon and water footprint, residual hazards, other life cycle stages and impacts, degrees of biodegradability, FDA and medical compliance, and quantification of the adjectives used to describe materials need to be addressed. Inclusion of these data will need more thorough research. As stated before, it is difficult to obtain all the direct and residual hazards along with the carbon and water footprint across the material's life cycle stages since they are very process dependent and would require more thorough sources to capture the data. Moreover, degrees of regulatory compliance and quantification of adjectives to describe material would need more investigation. Regulatory compliance data are often buried within the material supplier's website and can be obtained with more research, yet the adjectives used to describe a material are harder to obtain. They would require calling the material supplier and obtaining the necessary data, if they have it available and are willing to share it. The list above provides the specifications for creating a platform that can influence material sustainability decisions in the future, wherever they are made in the organization.

6.5 Result Visualizations and Testing After Iteration

Finally, the last feedback received was to think of a better graphic display of the results. Although mentioned by most of the test users, this was especially emphasized by the tool experts. According to them, material decisions are made in a maximum of 60 seconds, and usually more around 10 to 15 seconds. In order to create a useful tool, it must create a user experience and be designed with the user in mind. A designer or engineer does not have time to go through the data presented in tables and look at the multiple endpoints and map the tradeoffs between the materials, rather the tool must provide them with a quick visual guide.

A simple representation of results that allows the user to quickly make appropriate tradeoff choices among the search criteria was attempted. Figure 6.10 is an example of one of the proposed results display page. It is a radar chart divided into 4 sections; cost, yield strength as an example of a mechanical performance property, and both VOC and UFP emissions to represent material sustainability data. These are the important criteria that tradeoffs need to be made between during the material decision making process. The mechanical or performance property in the radar chart can be changed according to the property of interest for the user. Moreover, as can be seen in Figure 6.10, the data point for yield strength is plotted as one over the yield strength. This was done in order to keep consistency when reading the radar chart. Usually, lower price, VOC and UFP emissions are desired whereas higher yield strength is also desired. Thus, plotting one over the yield strength signifies that a lower number means a higher yield strength. Therefore, when looking at the radar chart, any data points that are closer to zero are the best options for all four categories. It is important to note that qualitative search criteria such as color and aesthetic options, regulatory compliance, and material adjective descriptions, do not show up on the chart output display. Since they are specified at the entry point of the search tool, the material outputs meet these requirements and thus the display aims to represent the other data that have tradeoffs to be made.

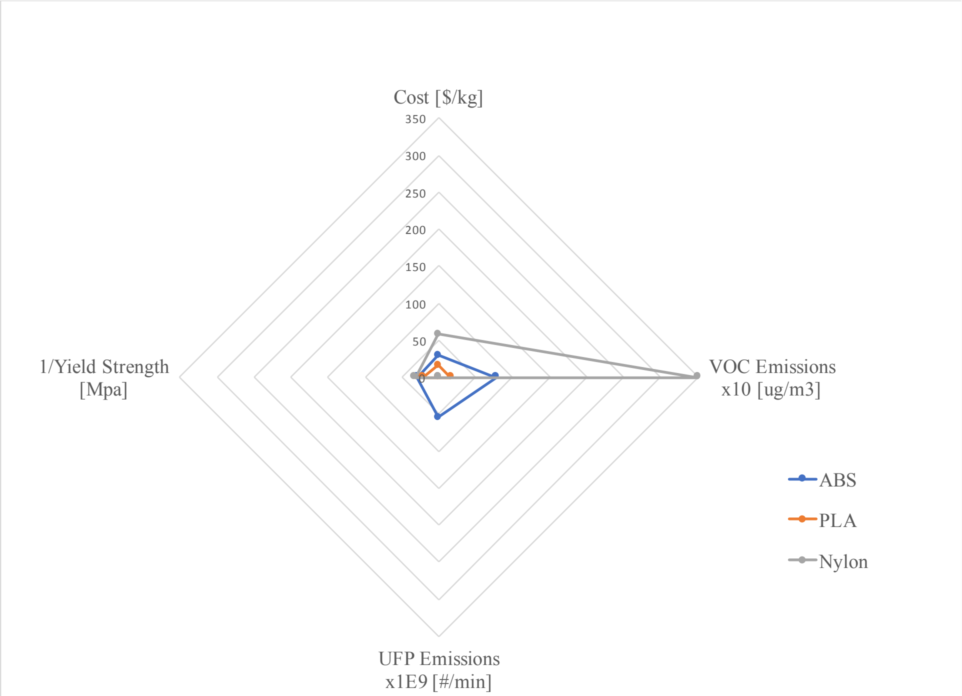


Figure 6. 10 Display of material results in a radar chart. Cost data is obtained from MatterHackers [150], the yield strength from the material supplier, and the VOC and UFP data from Azimi et al [139]

The purpose of this chart is to not only map the tradeoffs between costs, mechanical properties and sustainability data, but to also act as a first screen during the materials selection process. The empirical research conducted for this study showed that users want to simply know when a material they are using is over its exposure limit, thus causing them harm. Therefore, the radar chart in Figure 6.10 aims to address that concern. It plots the sum of all the VOC emissions per material. It does not distinguish between what VOCs are emitted from the material and in what quantities per VOC, yet the VOC emission dot can be color coded in either red or green. The green dot would indicate none of the VOCs released in the material are over their threshold limit, whereas a red dot would indicate one or more VOCs are over the limit. The same logic can hold for the UFP emissions. If they are over the threshold limit for particulate matter, then the data point can be color coded in red, if they are under then the data point can be coded in green.

If a user is strict with safety, Figure 6.10 could act as a screen, any material with a red VOC or UFP dot will simply not be used. If a user wants to know more about the emissions, they would then have to click on the data point in order to pull up more information. This information would include all the VOCs released, in what quantities, what their threshold limits are, and what hazards are associated with the VOCs. Visualizations that represent this data are shown below, yet are not plotted on a radar chart. No additional information is needed about UFP emissions.

The first safety scenario where materials over the UFP or VOC limit are eliminated from use is the most ideal. Initially, when setting up the tool, any “red list” materials, such as materials with VOCs over their threshold limit were going to be screened out so that the remaining choices below the threshold would be plotted. Yet some interviewees indicated they would like to know all the materials that meet their requirements and allow them to make a value judgment on the hazards they present and the safety control they may be able to implement to avoid them. Therefore, the materials with hazards over their limits were kept in the results, which allowed for a more flexible tool that meets the various needs of different users.

Figure 6.11 and Figure 6.12 display bar graphs plotting the same data in different ways. Figure 6.11 separates the categories on the x-axis by price, VOC emissions, and UFP emissions whereas Figure 6.12 separates the data according to the material of interest. As can be seen, the mechanical performance property of interest is not plotted here because it is dependent on the property of interest to the user, although it easily could be. Moreover, more than one performance property could be added in the bar graph.

The bar graphs are an alternate visualization to the radar charts. Again, the VOC emissions of each material are just the sum of the total emissions. Yet the detail on the type of VOCs and quantities released per VOC are not there in order to simplify the bar graph and allow users to get a quick sense of the total VOC emissions released. To maintain the simplicity of the bar graph and add one more layer of detail, the bars could be color coded in green or red to indicate if one or more VOC is under over the threshold limit respectively. More data will then have to be obtained if the bar is red. This visualization is shown in Figure 6.13. As for the UFP emissions, a horizontal line can simply be drawn on the graph to indicate the acceptable threshold limit, and if the bar graph is over the limit line, then it indicates that the UFP emissions for that material are too high. This line was not plotted since the ultrafine particles are reported in units of number of UFPs per minute (#/min) while particulate matter limits are given in micrograms per meter cube (ug/m3). Although the volume of the chamber used in the study from Azimi et al is known, more data would be needed on the density, shape, and volume of the UFP to convert particle count to micrograms.

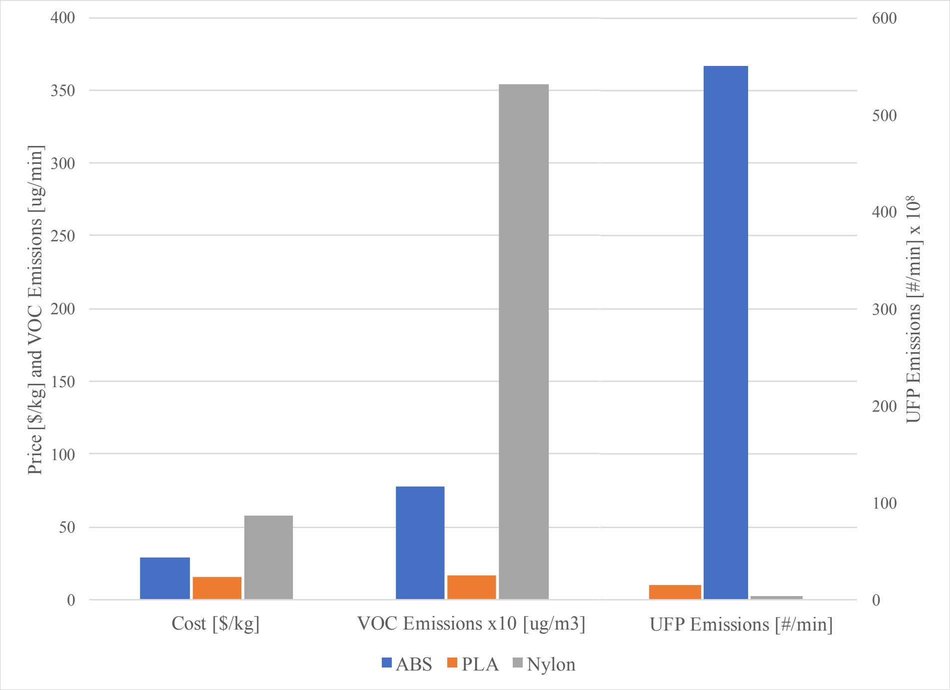


Figure 6. 11 Display of material results as a bar graph, version 1. Cost data is obtained from MatterHackers [150] and the VOC and UFP data from Azimi et al [139]

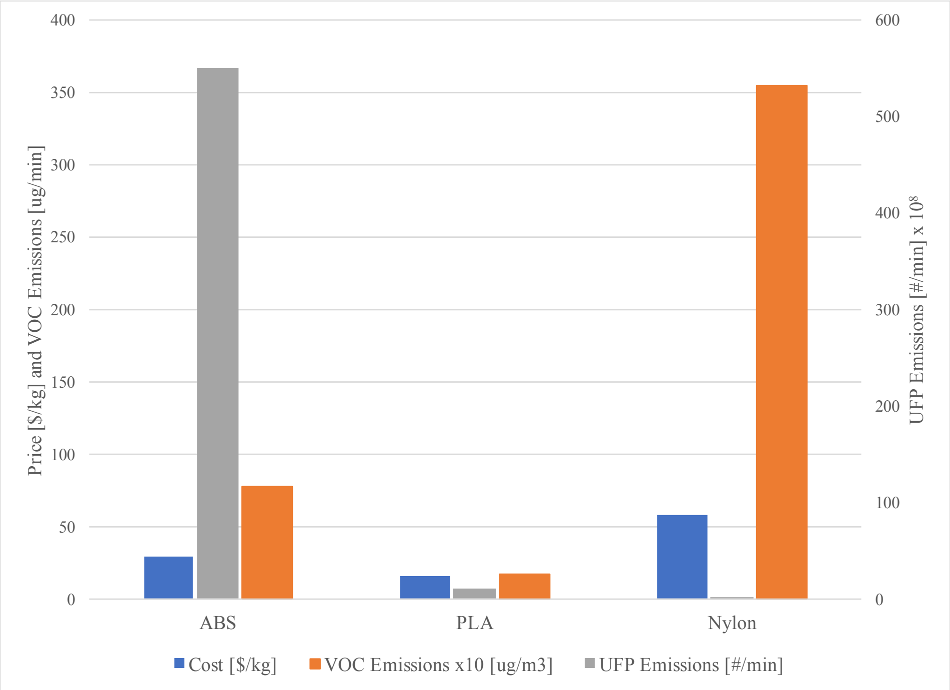


Figure 6. 12 Display of results as a bar graph, version 2. Cost data is obtained from MatterHackers [150] and the VOC and UFP data from Azimi et al [139]

VOC	Emission [mg/m^3]	NIOSH REL TWA Limit [mg/m^3]
Caprolactam	3	1
Hexanal	0.13	180
Octanal	0.05	Data Unavailable

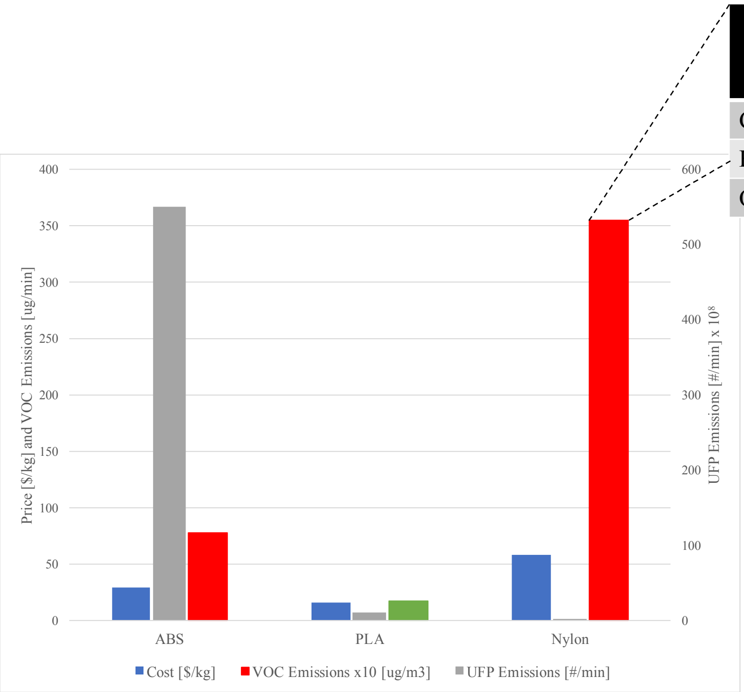


Figure 6. 13 Display of results as a bar graph, version 3. Cost data is obtained from MatterHackers [150], the VOC and UFP data from Azimi et al [139], and TWA limits from NIOSH [173][174]

As mentioned above, any bar that is color coded in red in Figure 6.13 indicates one or more of the VOCs emitted are over their exposure limit. When a user hovers over the material of interest, a breakdown of the VOCs emitted their emission rate and the recommended exposure limit (REL) using a time weighted average (TWA) set by The National Institute for Occupational Safety and Health (NIOSH) is reported. The data are reported from NIOSH since it researches and recommends the standards that are then reported as the required regulations from OSHA [170]. It is important to note that the VOC emission rate from the material sample is not directly translated into TWA limits. TWA represents the average exposure threshold limit based on an eight hour work day, 40 hour per week work schedule [175]. In order to calculate TWA, the sum of the level of the substance released in a time period multiplied by that time period is divided by the eight-hour work period (Equation 6.1) [175], [176]. The time period where the substance released was measured cannot exceed eight hours. For this case, the printing duration of the Nylon filament was roughly 3 hours and it is assumed that the VOC emission rate was measured over that period. Therefore, Equation 6.2 calculates the REL TWA for Caprolactam and indicates it is equal to 1.125 mg/m^3 which is greater than the NIOSH REL TWA of 1 mg/m^3.

$$TWA = \frac{\sum_{i=1}^{n} t_i \times c_i}{8\ hours} \tag{6.1}$$

Where

ti: time period
ci: concentration

$$TWA_{Caprolactam} = \frac{3\ hours\ \times\ 3\frac{mg}{m3}}{8\ hours} = 1.125\frac{mg}{m3} \tag{6.2}$$

Finally, Figure 6.14 attempts to address the information lacking from the other graphs and concentrates specifically on the VOC emissions per material. Again, the emission data was obtained from Azimi et al. [141]. In this graph, each material is labeled on the x-axis and their respective VOC emissions are plotted vertically above the label. In this case, the three most emitted VOCs from every material is plotted, although more data can be added. Each VOC is plotted using a specific shape. Moreover, if the VOC is under its threshold, then it is color coded in green, otherwise if it is over its threshold, it is colored in red. For example, in Figure 6.14, ABS emits styrene, hexanal, and octanal VOCs, yet only styrene is emitted in quantities above its REL TWA exposure limit.

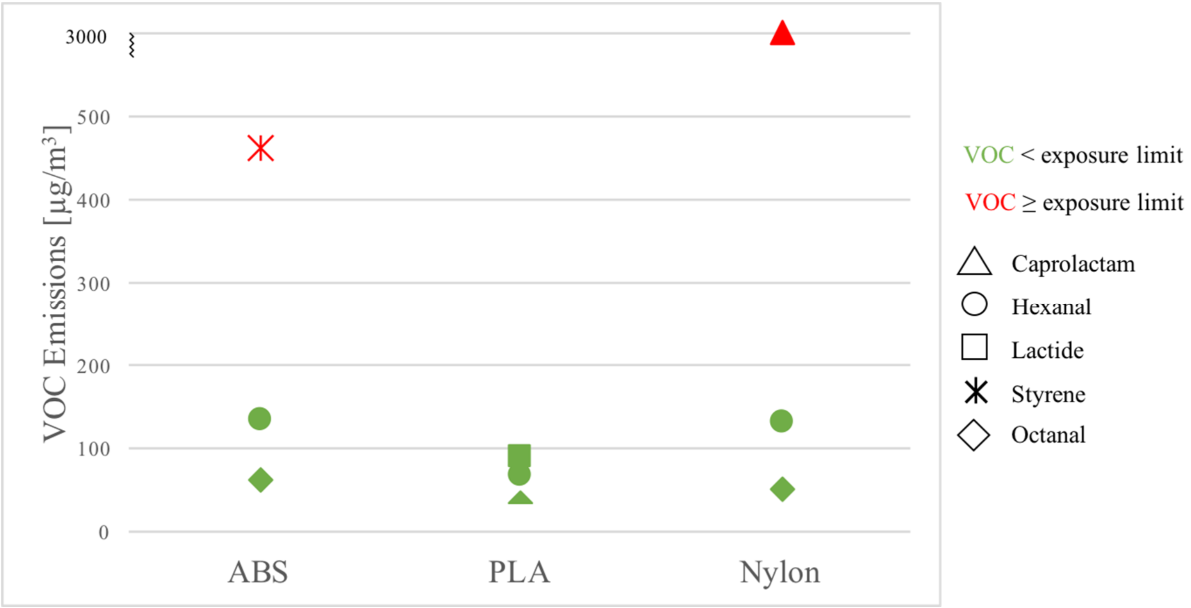
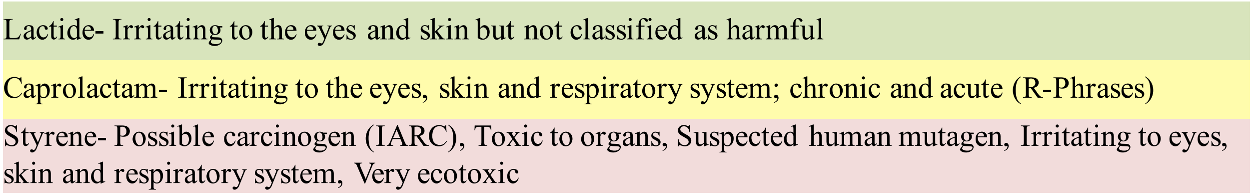


Figure 6. 14 Display of VOC emissions from material results

Although Figure 6.14 addresses the VOC emission data per material, Figure 6.15 goes one step further and lists the hazards associated with each VOC and color codes the VOC description according to the level of concerns associated with them, as suggested by one of the users during the first round of testing. Green represents a VOC with a low hazard concern, yellow represents a medium hazard, whereas red represents a high hazard concern. Figure 6.15 could be added into the results page in two ways, either as a pop-up of the VOC hazards from hovering over a particular filament, or as a table underneath Figure 6.14.



🟩 Lactide- Irritating to the eyes and skin but not classified as harmful

🟨 Caprolactam- Irritating to the eyes, skin and respiratory system; chronic and acute (R-Phrases)

🟥 Styrene- Possible carcinogen (IARC), Toxic to organs, Suspected human mutagen, Irritating to eyes, skin and respiratory system, Very ecotoxic

Figure 6. 15 Display of hazards associated with VOC emissions, not specific to a material from Figure 6.13. The purpose of this figure is to visually represent VOCs with a low, medium, and high hazard

Either the radar chart or the bar chart along with the information presented in Figure 6.14 and Figure 6.15 would provide a designer and engineer with all the information needed to help make an informed material decision in a time constrained and realistic manner. These figures were presented to some of the same users that initially tried the tool. Some users preferred the radar chart while others preferred the bar chart. Therefore, the tool could contain both options for users to choose their preference, therefore facilitating sustainable material decisions based on the ease of use of the chart for the user.

6.6 Specifications for Creating a Future Tool

This research used empirical interview data to understand how material decisions are currently made in industry and inform the inputs that a user would want to see on a material search tool. The user inputs were translated into a user interface on a tool. The process to convert user inputs to material outputs that meet specifications, was programmed in Excel for this research. The process translates and searches through data inputs provided. The data inputs for this research included information from MatterHackers, material supplier's websites, MSDS sheets, Pharos, and research papers to inform material costs, performance data, aesthetics data and sustainability data. Finally, the outputs from the Excel process programmed in the tool were visualizations of the basic trade-offs between materials that users are interested in. Figure 6.16 summarizes the relationship described.

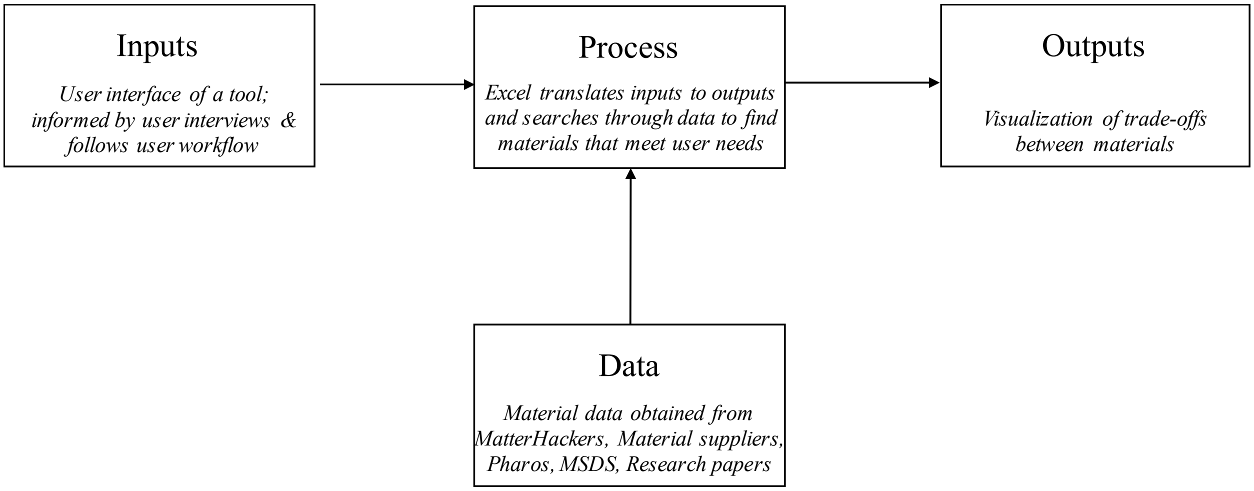


Figure 6. 16 Relationship between inputs, process, outputs, and data used to inform safer selection of materials for this research

Creating the tool established a set of specifications for building a platform to inform safer material selection in the longer run. The overarching constraints to fully develop such a tool moving forward are the multiple limitations from the data collection described in Chapter 5. Yet, other lessons were learned, described below.

Inputs

One important lesson learned from creating the tool is to focus on the audience that will be using the tool. This audience will dictate the input and output criteria of the tool. For this work, the tool focused specifically on helping designers and engineers make better material decisions. It aimed to map the trade-offs between costs, performance, aesthetics and sustainability while still maintaining regulatory compliance. The intention of this tool was to integrate it into design decisions from the start, so the product development team and the operations management/engineering team could propose designs and iterate on the design itself and not worry about material decisions. Once the critical components and performance issues were outlined, the tool could be used to suggest materials that addressed their material performance, cost, and aesthetics criteria and integrated material sustainability. Referring back to the user workflow, Figure 6.17 displays the area the tool focused on: the product development team and the operations management/ engineering team. Yet as the research progressed, it became clear that this scope of work places a limit on the influence of material sustainability within a company's workflow. Rather than concentrating on the operations management/engineering team, focusing on the company's strategy, for example, will change the way their supply chains operate and more broadly how they manage material choice decisions. This is discussed further in Chapter 7.

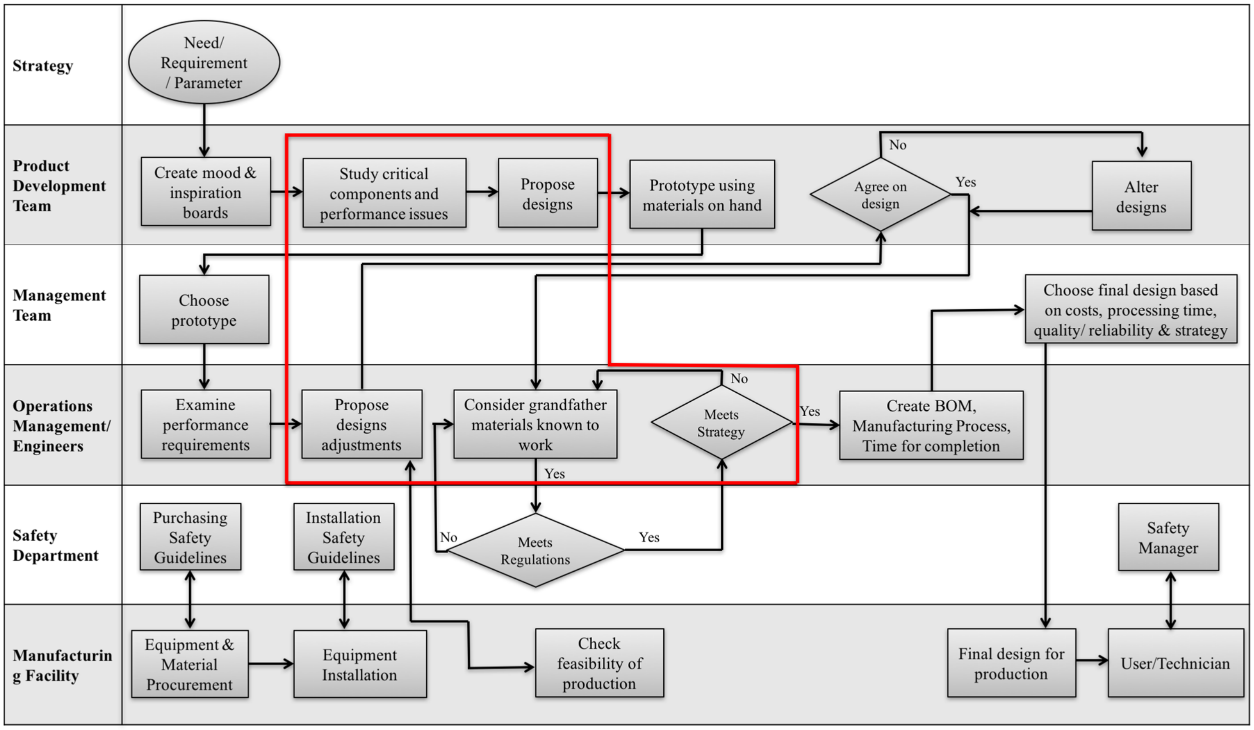


Figure 6. 17 Focus of the tool in the user workflow in the product development process

A future tool needs to focus on the audience in order to inform safer selection of materials in the first place, possibly at the strategy level in the organization. Such an audience could extend to include material and product manufacturers across the supply chain in some cases and will influence the inputs or criteria of interest.

Process

As mentioned previously, this tool was programmed in Excel. Yet the process of translating inputs to outputs using databases can be programmed and optimized in any software, not limited to Excel. Regardless of the software used, the main process is still composed of the same steps: take the inputs provided by a user, search through a database of material information for materials that meet the user's criteria, and output the resulting materials, as done here.

In addition to programming in a software, a future platform can optimize the search and translation of the data. For example, the process can limit the outputs of the search criteria. If the user indicates they do not want any hazardous material output from the search, then the process can act as a first screening step. As more data become available for making better informed trade-off decisions, programming could allow for more interpretation of the available data, or even the use of artificial intelligence or machine learning to augment the decision-making capability of the user. It may also become possible to create more layers of screening of materials that would allow for more refined recommendations.

Outputs

The output data is where a future platform will have room for change. The most important lesson learned that should be carried into a future tool is to be aware of the trade-offs between ease of use and simplicity of a visualization and the complexity of the data represented. As more data is obtained, or as inputs from the audience change, other important criteria will have to be displayed in the outputs. In addition, according to an interview mentioned earlier, a user makes decisions in less than 60 seconds. Therefore, the output of the tool must be visually simplistic and be easy to change according to the user's needs.

The inputs and outputs of this tool specifically concentrated on costs, performance, aesthetics, and sustainability of materials, as seen in Figure 6.18. These were the basic needs highlighted from the user interviews.

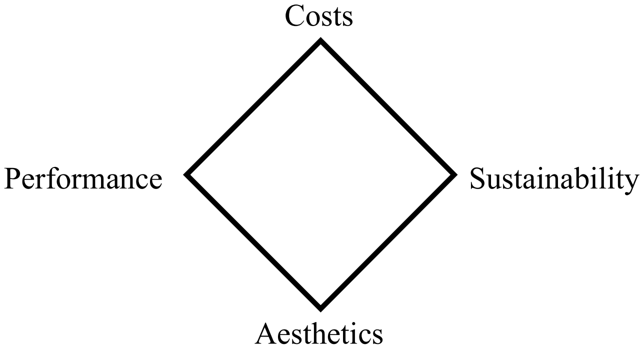


Figure 6. 18 Criteria analyzed for material selection in this research

As the feedback from users indicated, some users would like to see data on the water and carbon footprints of materials. Another interviewee noted they would like to integrate more safety control recommendations. Currently in the tool, general safety and exposure controls exist such as requiring proper ventilation, wearing respiratory and hand protection as well as safety glasses. Yet, as can be seen in Figure 6.19, a hierarchy of safety controls exist [177]. At the very least, the tool addresses personal protective equipment while the goal of the tool was to address elimination and substitution of materials that cause harmful exposure. For the short term, integrating more controls that fall under the administrative and work practice as well as engineering controls will increase the tool's effectiveness. If this data were to be included in output visualization, they would add a layer of complexity as seen in Figure 6.20. As more data is added, the more complex the visualizations and decisions become. Therefore, being aware of the balance between simplicity of visualization and complexity of the data will inform the outputs from a future platform to help facilitate more sustainable material decisions.

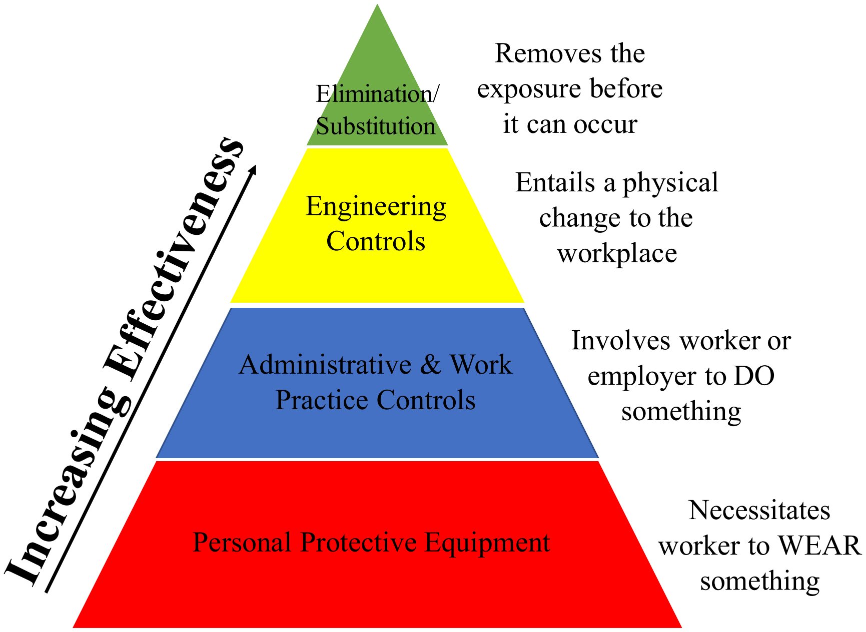


Figure 6. 19 Hierarchy of safety controls based on Green Chemistry Principle #12, American Chemical Society, adapted from Bradley et. al [177]

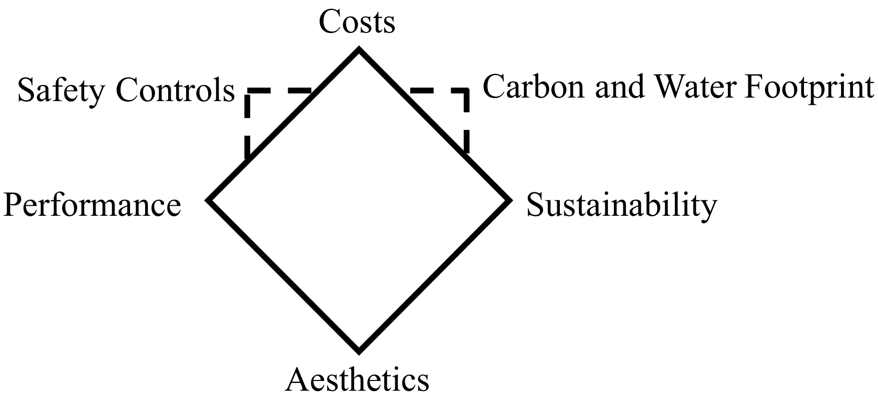


Figure 6. 20 Additional criteria to analyze in a tool adds complexity to a visualization

Chapter 7

Contributions and Future Work

The research presented here exposed fundamental issues relating to sustainable material selection during the design process. First, although product development diagrams aim to guide engineers and designers in companies to make systematic decisions in order to convert ideas into goods and services, they are not followed precisely. These product development processes are often written broadly in order to address multiple industries and the different constraints they face. Yet, addressing and understanding how products are being developed will help facilitate the integration of sustainability into the product design process.

In addition, this research revealed that material selection is a broken aspect in the product design process. Materials are chosen based on cost, performance and aesthetics, but rarely on the basis of their environmental or social impact. Moreover, little innovation occurs during the material selection process. Materials that have previously been known to work and meet regulatory compliance are often repeatedly used unless a change must occur. In order to integrate sustainability, the criteria currently being used to make material decisions must expand to include sustainability data. To do so, this data should be presented in an easy visual manner that preserves the user workflow and allows the user to make quick tradeoff choices among the criteria.

7.1 Contributions

The material database that was collected and created for this research is an important contribution. No database like this exists for FDM 3D printing materials. The database collected and synthesized data relating to the price, printing guidelines, mechanical properties, regulatory compliance, description and color availability of every FDM 3D printing material as well as all the hazard information and MSDS information available for every material. It also collected UFP and VOC emissions during printing of the materials and highlighted the different exposure limits that have been set by regulatory agencies.

Furthermore, the tool that was created and tested with potential users provides, in effect, a specification of what can be done for every industry to facilitate sustainable material decision making. It focuses on highlighting material costs, performance properties and sustainability data in a visual manner in order to help engineers and designers make appropriate tradeoffs among the criteria and ultimately create more sustainable products.

The biggest contribution from this research, however, is that it presented the multiple barriers that exist in order to integrate sustainability into the decision-making process. Barriers include messy and incoherent data collection methodologies, incomplete and missing material hazard data, understanding where in the material life cycle hazard impacts should be accounted for, and finally differentiating between different exposure limits set by different agencies. Highlighting these barriers notifies the industry of the importance of addressing them in order to truly achieve material sustainability in all industries.

7.2 Future Work

The research presented here covers a small aspect of sustainability for materials, specifically related to their hazards. Yet there is a whole ecosystem that has not been explored. Integrating a life cycle assessment of every material and their processing techniques, their energy and water consumption as well as the carbon emissions is just as important. Yet, this too is still a narrow focus. In order to truly understand sustainability of materials and final products, the manufacturing factory and the processes taking place in order to produce the final product should be examined. For the case of 3D printing materials, data on the 3D printer technology and the washing fluids used should be examined as well.

Furthermore, rather than being an optimization problem, as often viewed in the engineering literature, integrating sustainability demands a systems perspective that takes into account the many interactions among the variables involved. Figure 7.1 highlights the system. The model places the product to be designed in the center, identifies the key performance characteristics on which a product is evaluated – cost, performance and aesthetics – around it, and pulls out materials choice on the side. It then described the many other elements influencing the sustainable performance of the materials, and thus the product. Each material has 18 hazard endpoints relating to human health and the environment. Thus, in order to adopt a system view, the connections and interactions between every endpoint and the final four factors should be evaluated.

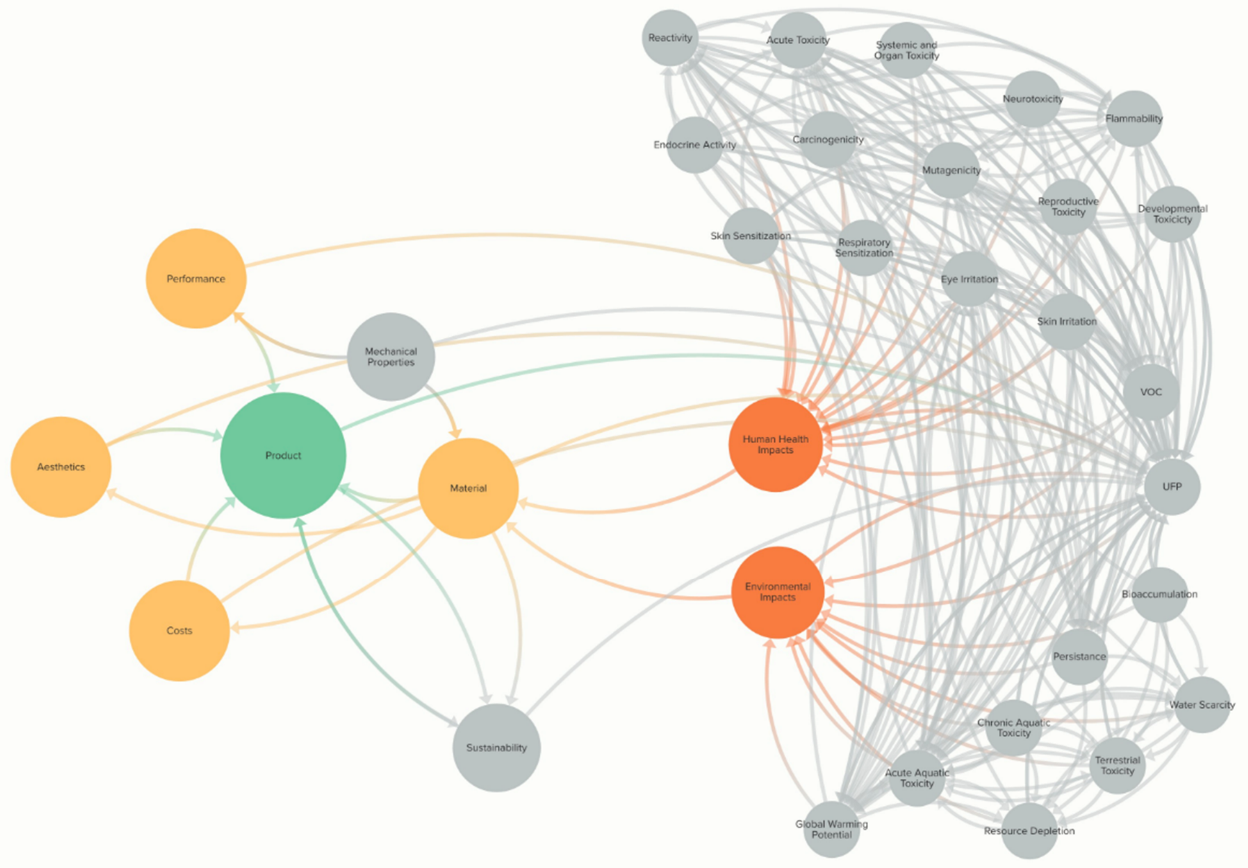


Figure 7. 1 System view of material sustainability

The most important factors that dictate a product are the material, performance, price and aesthetics. Yet material directly influences performance, price and aesthetics.

Understanding the dynamics of this system would allow a user to know how an improvement in one endpoint will affect the others. If the effect is positive on multiple endpoints and the four factors, then it is easier to make a decision. This systems view will truly help more thoroughly understand material sustainability and map the trade-offs between cost, performance, aesthetics and sustainability of materials in products. Yet in order to complete this system, broader and more pressing issues need to be addressed, as highlighted below.

Filling in Data Gaps

Much work is left for the future. The first overarching criteria is to fill in material hazard data gaps and transition towards better chemistry and materials. In order to do so, more R&D is required to understand and map the hazards associated with the materials. To facilitate this, there is a need for drivers for change. Such drivers can be an NGO or regulatory push, industry standards, or even monetary incentives and rewards for suppliers to know what is going into their materials. Such incentives could come from the manufacturers. As suppliers reveal the level of concern of their materials and start to address them, the more manufacturers are willing to work with them. This will further motivate others to start researching their materials and thus create a chain reaction.

Collaboration and collective action within the industry is also essential to drive down costs and build a thorough database of materials. The more players that join to research material data, the less it will cost one supplier to do so and the more it will scale. Moreover, if material databases for every industry are created and updated with material hazard information, it would result in the harmonization of the data being reported, better quality of data, accessible data for all the users, and lead to more sustainable accounting for industry products. This may seem unfeasible to some, yet it is already done in the automotive industry. The automotive industry has created a database of all materials used for automotive manufacturing, the International Material Data System (IMDS), and has become a global standard for OEMs and is used to insure suppliers are meeting the international standards, laws and regulations [178].

In addition, there is a need to promote, educate, and engage consumers to get involved with sustainability. Consumers can then pressure businesses to address negative materials within their products. Businesses, in turn, can demand suppliers to address their material hazards or stop working with them. This type of influence has worked in the cosmetics industry with the Campaign for Safer Cosmetics. The Campaign for Safer Cosmetics has educated people about toxic chemicals in their cosmetics, encouraged companies to disclose their ingredients, and allowed retailers to put pressure on the brands they sell to eliminate chemicals of concern [179].

Lastly, innovation challenges that reward solutions within industry will also help address gaps in material sustainability. Although not as scalable, it has proven to work. For example, Patagonia released a challenge to replace the use of perfluorinated compounds (PFC) that are used in waterproof clothing, yet are toxic and contaminate natural areas. Seventy-four teams across the US participated in this challenge giving Patagonia a list of scientific alternatives that they are now exploring [180].

Updating and Expanding the Tool

The second challenge to address in the future is how to keep the tool updated with material data information. As more research is done on material hazards, and as the tool expands to other industries, it will be difficult to continue manually collecting and reporting the data in the tool's database. Thus, artificial intelligence (AI) should be taken advantage of. As data mining and machine learning are growing, they should be used in order to search for data on the web and learn how to read and interpret hazard data reported. When interpreting the data, it is crucial that the quality of data is evaluated. Finally, the AI can determine what data is relevant and update the master database with the new information.

Encouraging Supply Chains to Comply

As stated above, businesses can encourage their supply chains to participate in material hazard research and incentivize them to create safer material formulations. Companies, especially chemical companies, are very traditional in their business ways and resist change that does not guarantee financial rewards. Yet if businesses can guarantee their partnership and even promote their suppliers through a green program, it could lead to more exposure for their suppliers to do business with others.

Another way to encourage suppliers would be to measure their impacts on human health and the environment, and communicate the value of moving towards more sustainable materials. If water usage, carbon emissions and other negative impacts from materials can be quantified and put in terms of costs, social issues, and the costs to clean up their hazards, it may educate and encourage suppliers to address their negative impacts.

In order to protect intellectual property, suppliers can outsource their material and chemical lists to third party reviewers that conduct a hazard assessment and provide each of their materials with a sustainability score. The third-party reviewer then eliminates the CAS numbers or any identifiers that were given to them, and shares the material scores with the businesses that work with those suppliers. The reviewed materials will fall into one of three categories; safe to use, use but needs improvement, and unsafe/phase out. This allows businesses to understand the hazards going into their products and engage with their suppliers on finding safer alternatives. Suppliers that are unwilling to share their information will lose the company's business.

One company that is engaged in such a program is Levi Strauss. Currently, they have 20 suppliers participating and screening their chemicals. Although met with resistance at first, Levis promised some participating companies that if their profits did not increase in a year after they have screened their chemicals, then Levis will pay them the difference. No supplier has needed to take that offer [52]. This proves that a company can encourage and influence their supply chain to comply while also benefiting their suppliers.

Leadership

Finally, the most important step to adopt material sustainability into a business has to come from proactive leaders of a company [29], [52]. As discussed in Chapter 6, this research focused on helping designers and engineers make more sustainable material decisions. Yet, more departments and people are involved during the product design process and decisions are being made in every department. As this research progressed, it became clearer that there is a need for a deeper understanding on how and where decisions are happening in order to achieve and integrate material sustainability at every level within the workflow.

In order to get a better understanding, sustainable companies such as Patagonia, Levi Strauss, and Seventh Generation were studied. Such companies promote sustainability in their strategy. Patagonia's mission statement incorporates a commitment to reducing social and environmental harm [181]. In doing so, every decision they make takes this commitment into account and thus flows through every department within their product design workflow. Through their book, The Responsible Company [181], Patagonia recommends companies to engage their team to find out what is the worst things that the company is doing, what it will cost and how it affects profits, and what is the easiest way to correct these problems. Then they recommend to prioritize the list and determine what will be done first and how much time, money, and people it will involve in order to correct. Patagonia argues that as a company corrects their mistakes, they will learn more and become more aware of their social and environmental impacts. This in turn will enable the company to create better quality business and products and share their learnings to influence others such as suppliers, trade associations, stakeholders, key customers, and key competitors. Patagonia implemented and learned from this system and created a checklist of items a company can follow to benefit a business, workers, costumers and community, and nature.

Levi Strauss is committed to minimizing the human health and environmental impacts of its clothing manufacturing processes and eliminating the industrial releases of hazardous chemicals into the environment. It's mission statement also focuses on sustainability and protecting their workers and planet. In order to do so, Levi's are screening chemicals using a hazard assessment before they enter their supply chain, thus eliminating any hazards before they can present a risk [52]. Moreover, they have shifted from a restricted substance list to a manufacturing substance list. Therefore, instead of restricting the chemicals used to finish products such as the RSL does, it restricts chemicals used in their entire facility. Finally, they have created the industry's first discharge wastewater quality guidelines.

Seventh Generation's mission statement is also focused on producing products that are safe for their customers, their families in their homes, and the environment. They want to reduce their environmental impact and increase performance and safety. To do so, they do not use any chemicals of concern. Moreover, if a chemical is deemed to be harmful, they will not use it in their product. In order to be accountable, they also report every chemical that goes into their product and are very transparent. They require their manufacturers and suppliers to meet their specifications or will not use them.

The common theme between these companies is the commitment they have to using less harmful chemicals and materials in order to create safer products that do not harm their customers or the environment. Thus, their mission and strategy flows throughout their company. Suppliers are screened before designers and engineers can even make material decisions. This allows their designers and engineers to focus on the performance of the material that meets their strategy rather than their sustainability. Material sustainability was already taken into account during the screening process. This provides a different view of integrating sustainability into the material decision-making process, on a larger company scope.

Good leadership motivates employees to make a positive impact for the greater good. If the leaders make sustainability a core principle and priority of the company, it will influence not only their employees but their supply chain and others members they do business with. In the end, sustainability will be integrated into all their decisions in order to produce safer products for people with less environmental harm.

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Appendix A

Appendix

A.1 Chapter 1

The material presented below is available online from the sources referenced. It is included here to have a thorough representation of this body of research material in one place.

Design for X strategies, provided by Griffen et al. [15]

Design for Reuse and Recovery[e]	Design for Durability[b]	Design for Benign Waste Disposition[c]
Design for Abundance (Upcycling)[a]	Design for Disassembly[b], [d]	Design for Hazard Reduction[c]
Design for Materials Optimization[e]	Design for Repair & Upgrade[b]	Design for Manufacturability[c]
Design for Waste Efficient Procurement[e]	Design for Dematerialization[b]	Design for Maintainability[c]
Design for Deconstruction and Flexibility[e]	Design for Servicization/Servitization[c]	Design for Human Safety[c]
Design for Energy and Material Conservation[c]	Design for Revalorization[c]	Design for Human Capital[c]
Design for Natural Capital[c]	Design for Economic Capital[c]	Design for Product Recovery[c]
Design for Product Disassembly[c]	Design for Recyclability[c], [d]	Design for Release Reduction[c]

A.2 Chapter 2

Interview Questions

Starting with big picture:

1. What is your job?
2. How long have you been doing it?
3. How does this differ from your previous job?
4. How do you manage product development?
    a. Where do material choices fall?

Design & Material specific questions

1. May you please walk me through the process of how you design a product and choose a material?
    a. Tell me about the last time you chose a material

2. How often do you make material choice decisions during the product design process?

3. Where do you obtain the list of materials that can be used?
    a. Do designers have the freedom of choosing materials for products?
    b. Is there any hazard or sustainability information associated with the list of materials used to make decisions?

4. What criteria is a concern?
    a. Pricing
    b. Safety
    c. Specifications and quality
    d. Sustainability and impacts
    e. What regulatory safety measures do you meet? Are the required?

5. Who specifies these criteria?

6. What characteristics do you evaluate for materials?

7. Are there characteristics you would like to include but not available to you?

8. How do you evaluate the hazards associated with the materials you use?
    a. Do you perform your own tests?
    b. Is there software that is used to evaluate materials?
    c. Is an LCA or HA conducted?

9. How do you go about assessing what a toxic chemical is?
    a. How do you characterize toxicity
    b. Are there endpoints that you rank more importantly than others?

   c. What tools do you use to obtain toxic information or general material information (hazard bases only)?
   d. How do you deal with information gaps (ignore/negative/neutral)?
   e. How do you work towards eliminating toxic materials?

10. Do you perform LCA of materials or product?

11. Is the amount or use of a material taken into consideration (exposure)?

12. If there is no clear “winner” how do you decide which material to choose?

13. What would simplify the decision process?

14. How do you influence your supply chain to take out toxic substances?

15. If you find a hazardous chemical, do you work with companies/supply chain to find alternatives?
    a. If so, do you deal with designers of products?
    b. Could you walk me through an example?

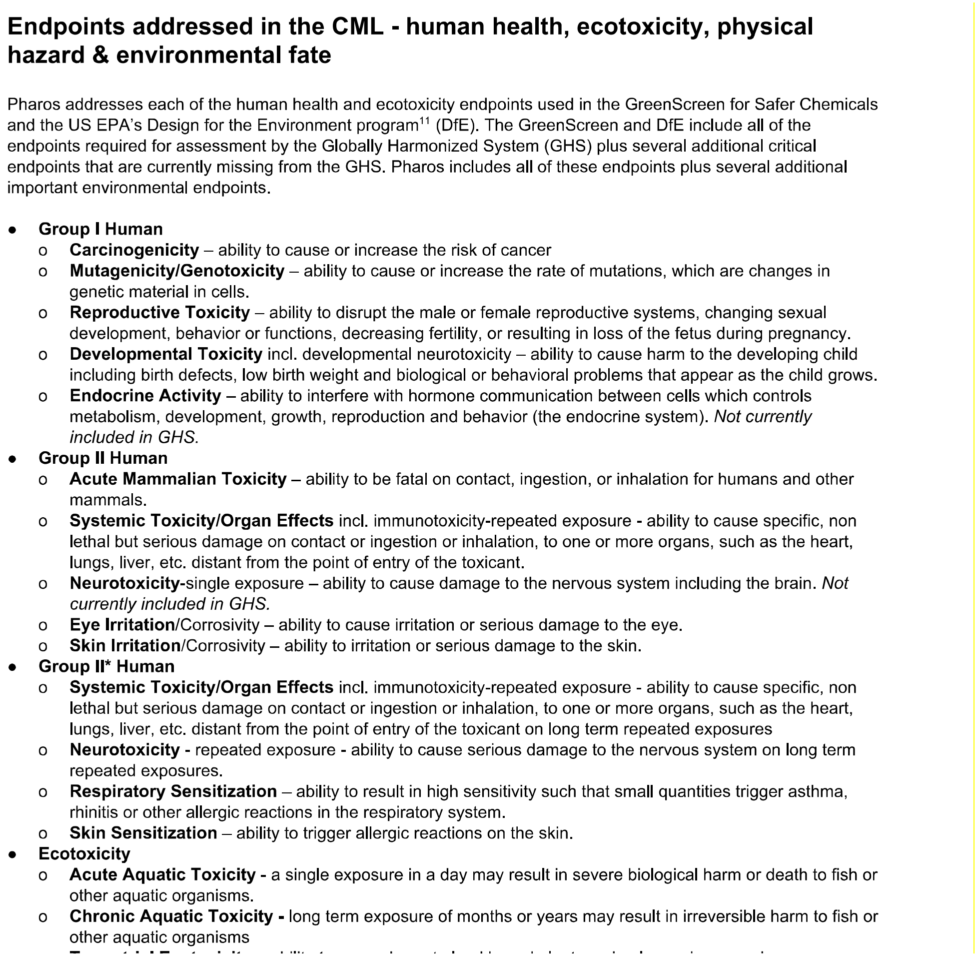
A.3 Chapter 3

No content.

A.4 Chapter 4

The material presented below is available online from the sources referenced. It is included here to have a thorough representation of this body of research material in one place.

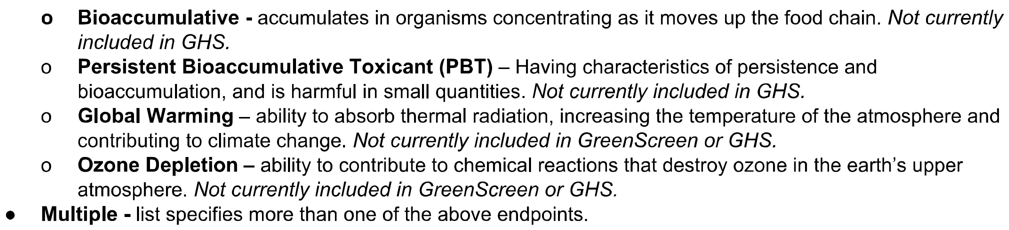
17]



Endpoints addressed in the CML - human health, ecotoxicity, physical hazard & environmental fate

Pharos addresses each of the human health and ecotoxicity endpoints used in the GreenScreen for Safer Chemicals and the US EPA's Design for the Environment program[11] (DfE). The GreenScreen and DfE include all of the endpoints required for assessment by the Globally Harmonized System (GHS) plus several additional critical endpoints that are currently missing from the GHS. Pharos includes all of these endpoints plus several additional important environmental endpoints.

- **Group I Human**
    - **Carcinogenicity** – ability to cause or increase the risk of cancer
    - **Mutagenicity/Genotoxicity** – ability to cause or increase the rate of mutations, which are changes in genetic material in cells.
    - **Reproductive Toxicity** – ability to disrupt the male or female reproductive systems, changing sexual development, behavior or functions, decreasing fertility, or resulting in loss of the fetus during pregnancy.
    - **Developmental Toxicity** incl. developmental neurotoxicity – ability to cause harm to the developing child including birth defects, low birth weight and biological or behavioral problems that appear as the child grows.
    - **Endocrine Activity** – ability to interfere with hormone communication between cells which controls metabolism, development, growth, reproduction and behavior (the endocrine system). *Not currently included in GHS.*
- **Group II Human**
    - **Acute Mammalian Toxicity** – ability to be fatal on contact, ingestion, or inhalation for humans and other mammals.
    - **Systemic Toxicity/Organ Effects** incl. immunotoxicity-repeated exposure - ability to cause specific, non lethal but serious damage on contact or ingestion or inhalation, to one or more organs, such as the heart, lungs, liver, etc. distant from the point of entry of the toxicant.
    - **Neurotoxicity**-single exposure – ability to cause damage to the nervous system including the brain. *Not currently included in GHS.*
    - **Eye Irritation**/Corrosivity – ability to cause irritation or serious damage to the eye.
    - **Skin Irritation**/Corrosivity – ability to irritation or serious damage to the skin.
- **Group II* Human**
    - **Systemic Toxicity/Organ Effects** incl. immunotoxicity-repeated exposure - ability to cause specific, non lethal but serious damage on contact or ingestion or inhalation, to one or more organs, such as the heart, lungs, liver, etc. distant from the point of entry of the toxicant on long term repeated exposures
    - **Neurotoxicity** - repeated exposure - ability to cause serious damage to the nervous system on long term repeated exposures.
    - **Respiratory Sensitization** – ability to result in high sensitivity such that small quantities trigger asthma, rhinitis or other allergic reactions in the respiratory system.
    - **Skin Sensitization** – ability to trigger allergic reactions on the skin.
- **Ecotoxicity**
    - **Acute Aquatic Toxicity** - a single exposure in a day may result in severe biological harm or death to fish or other aquatic organisms.
    - **Chronic Aquatic Toxicity** - long term exposure of months or years may result in irreversible harm to fish or other aquatic organisms



- **Bioaccumulative -** accumulates in organisms concentrating as it moves up the food chain. *Not currently included in GHS.*
- **Persistent Bioaccumulative Toxicant (PBT)** – Having characteristics of persistence and bioaccumulation, and is harmful in small quantities. *Not currently included in GHS.*
- **Global Warming** – ability to absorb thermal radiation, increasing the temperature of the atmosphere and contributing to climate change. *Not currently included in GreenScreen or GHS.*
- **Ozone Depletion** – ability to contribute to chemical reactions that destroy ozone in the earth's upper atmosphere. *Not currently included in GreenScreen or GHS.*
- **Multiple -** list specifies more than one of the above endpoints.

MSDS Heading and Descriptions, provided by GHS, United Nations [153]

Table 1.5.2 Minimum information for an SDS

1.	**Identification of the substance or mixture and of the supplier**	(a) GHS product identifier; (b) Other means of identification; (c) Recommended use of the chemical and restrictions on use; (d) Supplier's details (including name, address, phone number etc.); (e) Emergency phone number.
2.	**Hazards identification**	(a) GHS classification of the substance/mixture and any national or regional information; (b) GHS label elements, including precautionary statements. (Hazard symbols may be provided as a graphical reproduction of the symbols in black and white or the name of the symbol e.g. "flame", "skull and crossbones"); (c) Other hazards which do not result in classification (e.g. "dust explosion hazard") or are not covered by the GHS.
3.	**Composition/ information on ingredients**	**Substance** (a) Chemical identity; (b) Common name, synonyms, etc.; (c) CAS number and other unique identifiers; (d) Impurities and stabilizing additives which are themselves classified and which contribute to the classification of the substance. **Mixture** The chemical identity and concentration or concentration ranges of all ingredients which are hazardous within the meaning of the GHS and are present above their cut-off levels. ***NOTE****: For information on ingredients, the competent authority rules for CBI take priority over the rules for product identification.*
4.	**First-aid measures**	(a) Description of necessary measures, subdivided according to the different routes of exposure, i.e. inhalation, skin and eye contact and ingestion; (b) Most important symptoms/effects, acute and delayed. (c) Indication of immediate medical attention and special treatment needed, if necessary.
5.	**Fire-fighting measures**	(a) Suitable (and unsuitable) extinguishing media. (b) Specific hazards arising from the chemical (e.g. nature of any hazardous combustion products). (c) Special protective equipment and precautions for fire-fighters.
6.	**Accidental release measures**	(a) Personal precautions, protective equipment and emergency procedures. (b) Environmental precautions. (c) Methods and materials for containment and cleaning up.
7.	**Handling and storage**	(a) Precautions for safe handling. (b) Conditions for safe storage, including any incompatibilities.
8.	**Exposure controls/personal protection**	(a) Control parameters e.g. occupational exposure limit values or biological limit values. (b) Appropriate engineering controls. (c) Individual protection measures, such as personal protective equipment.
9.	**Physical and chemical properties**	(a) Appearance (physical state, colour etc); (b) Odour; (c) Odour threshold; (d) pH; (e) Melting point/freezing point; (f) Initial boiling point and boiling range; (g) Flash point; (h) Evaporation rate; (i) Flammability (solid, gas); (j) Upper/lower flammability or explosive limits; (k) Vapour pressure;

(Cont'd on next page)

Table 1.5.2 Minimum information for an SDS *(cont'd)*

9.	*Physical and chemical properties (cont'd)*	(l) Vapour density; (m) Relative density; (n) Solubility(ies); (o) Partition coefficient: n-octanol/water; (p) Auto-ignition temperature; (q) Decomposition temperature; (r) Viscosity.
10.	**Stability and reactivity**	(a) Reactivity (b) Chemical stability; (c) Possibility of hazardous reactions; (d) Conditions to avoid (e.g. static discharge, shock or vibration); (e) Incompatible materials; (f) Hazardous decomposition products.
11.	**Toxicological information**	Concise but complete and comprehensible description of the various toxicological (health) effects and the available data used to identify those effects, including: (a) information on the likely routes of exposure (inhalation, ingestion, skin and eye contact); (b) Symptoms related to the physical, chemical and toxicological characteristics; (c) Delayed and immediate effects and also chronic effects from short and long term exposure; (d) Numerical measures of toxicity (such as acute toxicity estimates).
12.	**Ecological information**	(a) Ecotoxicity (aquatic and terrestrial, where available); (b) Persistence and degradability; (c) Bioaccumulative potential; (d) Mobility in soil; (e) Other adverse effects.
13.	**Disposal considerations**	Description of waste residues and information on their safe handling and methods of disposal, including the disposal of any contaminated packaging.
14.	**Transport information**	(a) UN number; (b) UN proper shipping name; (c) Transport hazard class(es); (d) Packing group, if applicable; (e) Environmental hazards (e.g.: Marine pollutant (Yes/No)); (f) Transport in bulk (according to Annex II of MARPOL 73/78 and the IBC Code); (g) Special precautions which a user needs to be aware of, or needs to comply with, in connection with transport or conveyance either within or outside their premises.
15.	**Regulatory information**	Safety, health and environmental regulations specific for the product in question.
16.	**Other information including information on preparation and revision of the SDS**	

Hazard lists included in the CML

As of the publication date of this document, there were approximately 36,000 chemical, polymer and other material substances in the library. Over 25,000 of them are associated with at least one hazard warning. The following authoritative chemical hazard lists are currently scanned[12]:

1. **AOEC - Asthmagens (AOEC)** Association of Occupational and Environmental Clinics, AOEC Exposure Codes - Asthmagen List [2]
2. **Cal/EPA - Chemicals Known to Cause Cancer & Reproductive Toxicity (Prop 65)** State of California Environmental Protection Agency, Chemicals Known to the State to Cause Cancer or Reproductive Toxicity - California Proposition 65 - Safe Drinking Water and Toxic Enforcement Act Of 1986 [1]
3. **CHE - Toxicant Database (CHE)** ***(asthma & rhinitis only)*** Collaborative on Health and the Environment, Toxicant and Disease Database [3]
4. **ChemSec - Substitute List (SIN)** ChemSec, The International Chemical Secretariat SIN (Substitute It Now) List Version 2.0 [1]
5. **EC - CLP Inventory (EU CMR (2))** European Commission, Classification and Labelling Inventory – CMRs [1]
6. **EC - CLP/GHS Hazard Statements (EU H-Statements)** European Commission, Regulation on the Classification, Labelling and Packaging of Substances and Mixtures (CLP) Annex 6 Table 3-1 - GHS Hazard code criteria [1]
7. **EC - ESIS-PBT System (EU PBT)** European Commission, European chemical Substances Information System (ESIS) - PBT List [1]
8. **EC - Ozone depletion substances (EU Ozone)** European Commission**,** Regulation (EC) No 1005/2009 of the European Parliament and of the Council of 16 September 2009 on substances that deplete the ozone layer - Controlled substances and new substances [3]
9. **EC - Priority Endocrine Disrupters (EU ED**) European Commission, EU Community Strategy for Endocrine Disrupters - Priority List [2]
10. **EC - REACH Annex XVII (EU CMR(1))** European Commission, Restrictions On The Manufacture, Placing On The Market And Use Of Certain Dangerous Substances, Preparations And Articles - Carcinogens, Mutagens & Reproductive Toxicants [1]
11. **EC - REACH Substances of High Concern (EU SVHC)** European Commission**,** Substances of Very High Concern for authorisation - REACH Annex XIV [1]
12. **EC - Risk Phrases (EU R-Phrases)** European Commission, Substances with EU Risk & Safety Phrases (Commission Directive 67-548-EEC) [1]
13. **EC/Oslo-Paris Conv - Priority PBTs & EDs & equivalent concern (OSPAR)** Oslo-Paris Convention Commission, Chemical Lists of Priority Action & Possible Concern [1]
14. **EHP - San Antonio Statement on BFRs & CFRs (San Antonio)** Environmental Health Perspectives, San Antonio Statement on Brominated and Chlorinated Flame Retardants [3]
15. **Environment Canada - Domestic Substances List (DSL)** Environment Canada & Health Canada, Canadian Environmental Protection Act (CEPA) - Environmental Registry - Domestic Substances List (DSL) [1]
16. **German MAK - List of Substances (MAK**) MAK Commission of Germany (Deutsche Forschungsgemeinschaft), List of Substances with MAK & BAT Values & Categories [1]
17. **International Agency for Research on Cancer - Cancer Monographs (IARC)** International Agency for Research on Cancer, World Health Organization, Monographs On the Evaluation of Carcinogenic Risks to Humans [1]
18. **Japan METI/MOE - GHS Classifications (GHS-Japan)** Government of Japan, GHS Classifications [2]
19. **Korea NIER - GHS Classification (GHS-Korea)** Republic of Korea - National Institute of Environmental Research, GHS Classification and Labelling for Toxic Chemicals [2]
20. **Lancet - Grandjean & Landrigan Neurotoxic Chemicals (G&L Neuro)** Lancet: authors Philippe Grandjean & Phil Landrigan, Developmental neurotoxicity of industrial chemicals, List of 201 Chemicals known to be neurotoxic in man [2]

21. **New Zealand HSNO/GHS (GHS-New Zealand)**, New Zealand Environmental Protection Authority, New Zealand HSNO Chemical Classifications [2]
22. **Oregon DEQ - Priority Persistent Pollutants (OR P3)** State of Oregon Department of Environmental Quality, Priority Persistent Pollutant (P3) List [1]
23. **Patty's Toxicology - Boyes Neurotoxicants (Boyes-N)** Patty's Toxicology: author William K Boyes, Chemicals with occupational exposure standards based on nervous system effects (Boyes 2001) [2]
24. **Québec CSST - WHMIS Classifications (WHMIS**), Government of Québec, WHMIS-SIMDUT: Controlled Products Classifications [2]
25. **Quebec CSST Asthma Agents (Quebec Asthma)** Quebec Workplace Health and Safety Commission (Commission de la santé et de la securite du travail (CSST)), Agents Causing Occupational Asthma With Key References [3]
26. **Silent Spring - Breast Cancer Chemicals (SSI-BC**), Silent Spring Institute, Mammary Carcinogens Review Database [3]
27. **TEDX - Potential Endocrine Disruptors (TEDX)**, The Endocrine Disruption Exchange (TEDX), TEDX List of Potential Endocrine Disruptors [2]
28. **UNEP Stockholm Conv - Persistent Organic Pollutants (Stockholm)** United Nations Environment Programme, Stockholm Convention on Persistent Organic Pollutants (POPs) - Annex A, B & C and under Review [1]
29. **US CDC - Occupational Carcinogens (NIOSH-C)** US Centers for Disease Control**,** NIOSH Carcinogen List [1]
30. **US EPA - Extremely Hazardous Substances (EPA-AMT),** US Environmental Protection Agency, Extremely Hazardous Substances - EPCRA Section 302 [2]
31. **US EPA - Global Warming Potentials (EPA-GW)** US Environmental Protection Agency**,** Global Warming Potentials of Ozone Depletors and Substitutes [3]
32. **US EPA - IRIS Carcinogens (EPA-C)** US Environmental Protection Agency**,** Integrated Risk Information System Database (IRIS) [1]
33. **US EPA - OPP - Registered Pesticides (EPA-FIFRA) *(incomplete)*** US Environmental Protection Agency, Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) Registered Pesticides [3]
34. **US EPA - Ozone Depleting Substances (EPA-ODS)** US Environmental Protection Agency, Ozone-Depleting Substances (ODS) Class I & Class II [3]
35. **US EPA - PPT Chemical Action Plans (EPA Action)** US Environmental Protection Agency, Chemicals of Concern Action Plans [3]
36. **US EPA - PPT Priority PBTs (EPA PBT)** US Environmental Protection Agency**,** Priority PBT Profiles [1]
37. **US EPA - Priority PBTs (NWMP Priority)** US Environmental Protection Agency**,** Priority Chemicals List [1]
38. **US EPA – Toxics Release Inventory PBTs (TRI PBT**) US Environmental Protection Agency TRI PBT Chemical List [1]
39. **US NIH - Report on Carcinogens (NTP-RoC)** US Dept of Health & Human Services**,** 12th Report on Carcinogens [1]
40. **US NIH - Reproductive & Developmental Monographs (NTP-OHAaT)** US Dept of Health & Human Services, Expert Panel Reports & Monographs on Reproductive and Developmental Toxicity [1]
41. **Washington DoE - PBT (WA PBT)** State of Washington Department of Ecology, Chapter 173-333 WAC Persistent Bioaccumulative Toxins [1]

[1] Lists included in the GreenScreen List Translator for which some of the sublists are assessed as Likely Benchmark 1
[2] Additional lists included in the GreenScreen List Translator
[3] Lists which are not yet included in the GreenScreen List Translator

All substances on each of these authoritative lists are included in the Pharos CML if a CAS number was provided by the list issuer. When no CAS number was provided, Pharos staff has exercised professional judgment to associate a CAS number where possible. Poorly defined substances with no CAS number association are not included in the CML at this time.

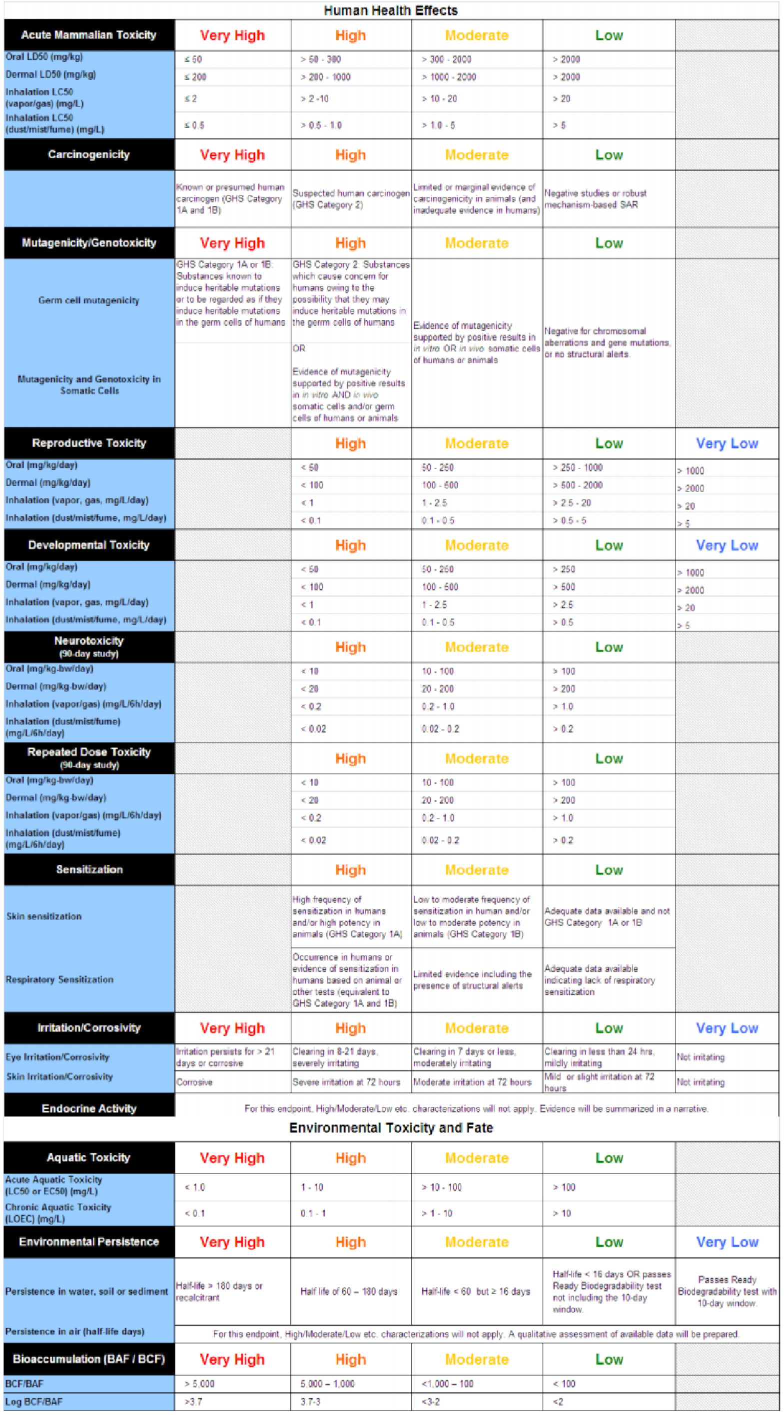
Some of the lists reference **compound groups**, groups or classes of chemicals with a common element that leads to them all to share similar hazards, such as lead based compounds. This is in addition to or instead of identifying

RSL lists currently scanned include:

1. **C2C Banned Chemicals** Cradle to Cradle Product Innovation Institute (C2CPII), Banned Lists of Chemicals in the Cradle to Cradle Certified Product Standard **-** Version 3.0
2. **CA SCP Candidate Chemicals Department of Toxic Substance Control (DTSC), Safer Consumer Product Candidate Chemicals**
3. **EC - PACT-RMOA Substances (EU PACT)** European Commission, Public Activities Coordination Tool for Risk Management Option Analysis
4. **EC - REACH Exemptions** European Commission, Commission Regulation (EC) No 987/2008 Annex I & 2 Exemptions from the Obligation to Register in accordance with REACH article 2(7)a
5. **EC - ROHS** European Commission, Directive on the Restriction Of the use of certain Hazardous Substances

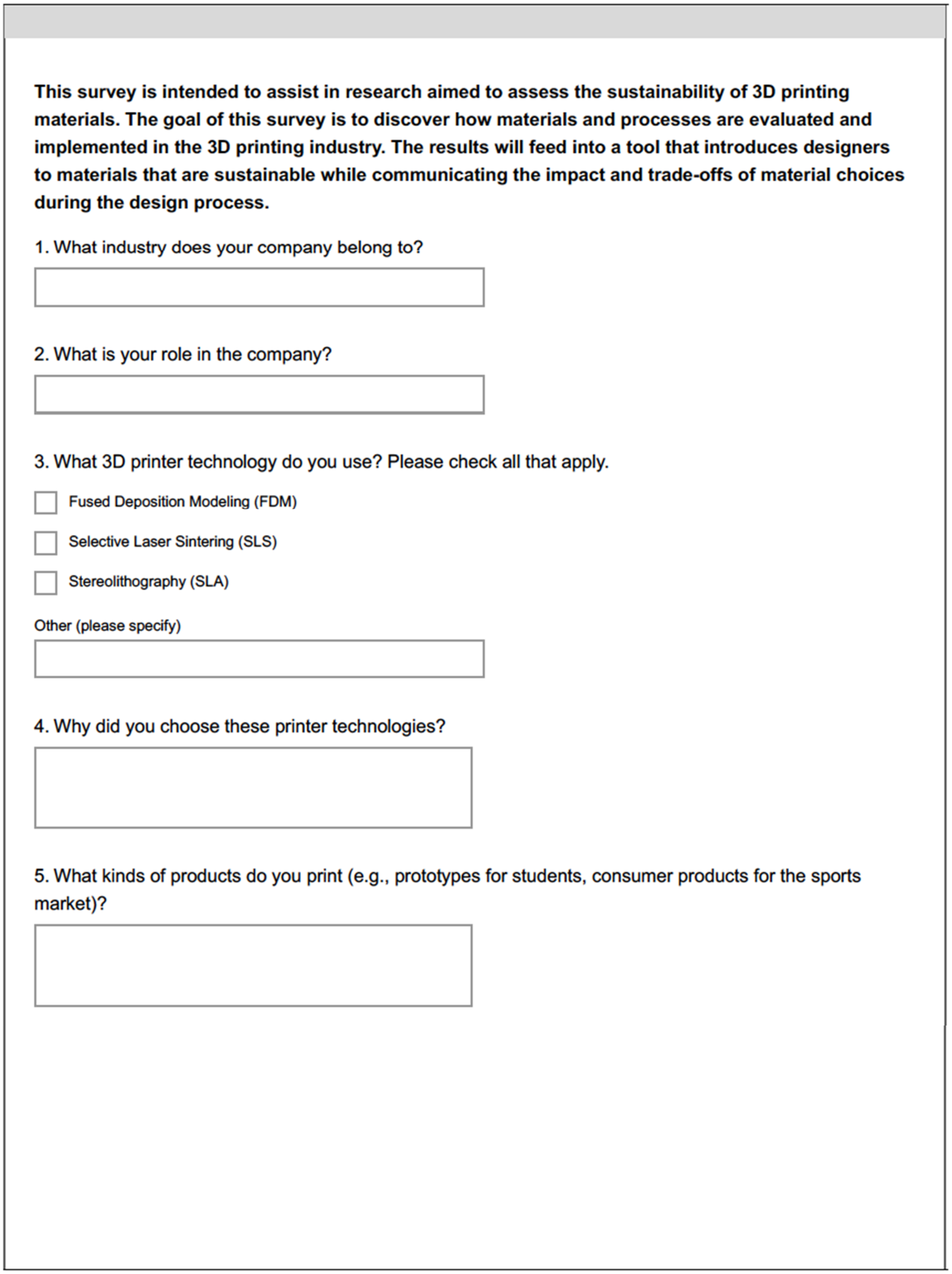
7. **Environment Canada - Virtual Elimination List (CEPA)** Environment Canada & Health Canada, Canadian Environmental Protection Act (CEPA) - Environmental Registry - Virtual Elimination List
8. **German FEA - Substances Hazardous to Waters (VwVwS)** German Federal Environment Agency, Administrative Regulation on the Classification of Substances hazardous to waters into Water Hazard Classes (Verwaltungsvorschrift wassergefahrdende Stoffe)
9. **Hazardous 100 (SCHF)** Safer Chemicals, Healthy Families, Hazardous 100+ List of Chemicals of High Concern
10. **HBN - Priority Asthmagens** Healthy Building Network, HBN Priority Building Material Asthmagens List
11. **Living Future - Living Building Red List (ILFI Red)** International Living Future Institute Living Building Challenge 2.1 - Red List of Materials & Chemicals
12. **Living Future - Living Building Red List (ILFI Red)** International Living Future Institute Living Building Challenge 3.0 - Red List of Materials & Chemicals
13. **P+W - Precautionary List** Perkins+Will, Precautionary List
14. **Rotterdam Conv - Annex III (PIC)** United Nations Environment Programme**,** Rotterdam Convention Prior Informed Consent (PIC) Annex III Chemicals
15. **US EPA – DfE SCIL** US Environmental Protection Agency, Safer Chemical Ingredients List (Positive List)
16. **US EPA - Exempt VOCs** US Environmental Protection Agency, VOCs exempt from smog regulation because of negligible photochemical reactivity
17. **US EPA - Hazardous Air Pollutants** US Environmental Protection Agency, Clean Air Act Amendments of 1990 List of Hazardous Air Pollutants
18. **US OSHA – Carcinogens** US Department of Labor**,** TRI Carcinogens
19. **USGBC - LEED Credits (LEED)** US Green Building Council, LEED Credits: Chemical Avoidance in Building Materials

EPA Design for the Environment Alternative Assessment Criteria for Hazard Evaluation Data Limits per Hazard Category, provided by Office of Pollution Prevention and Toxics, U.S. Environmental Protection Agency [121]



Human Health Effects					
Acute Mammalian Toxicity	Very High	High	Moderate	Low	
Oral LD50 (mg/kg)	≤ 50	> 50 - 300	> 300 - 2000	> 2000	
Dermal LD50 (mg/kg)	≤ 200	> 200 - 1000	> 1000 - 2000	> 2000	
Inhalation LC50 (vapor/gas) (mg/L)	≤ 2	> 2 -10	> 10 - 20	> 20	
Inhalation LC50 (dust/mist/fume) (mg/L)	≤ 0.5	> 0.5 - 1.0	> 1.0 - 5	> 5	
Carcinogenicity	Very High	High	Moderate	Low	
	Known or presumed human carcinogen (GHS Category 1A and 1B)	Suspected human carcinogen (GHS Category 2)	Limited or marginal evidence of carcinogenicity in animals (and inadequate evidence in humans)	Negative studies or robust mechanism-based SAR	
Mutagenicity/Genotoxicity	Very High	High	Moderate	Low	
Germ cell mutagenicity	GHS Category 1A or 1B: Substances known to induce heritable mutations or to be regarded as if they induce heritable mutations in the germ cells of humans	GHS Category 2: Substances which cause concern for humans owing to the possibility that they may induce heritable mutations in the germ cells of humans	Evidence of mutagenicity supported by positive results in *in vitro* OR *in vivo* somatic cells of humans or animals	Negative for chromosomal aberrations and gene mutations, or no structural alerts.	
Mutagenicity and Genotoxicity in Somatic Cells		OR Evidence of mutagenicity supported by positive results in *in vitro* AND *in vivo* somatic cells and/or germ cells of humans or animals			
Reproductive Toxicity		High	Moderate	Low	Very Low
Oral (mg/kg/day)		< 50	50 - 250	> 250 - 1000	> 1000
Dermal (mg/kg/day)		< 100	100 - 500	> 500 - 2000	> 2000
Inhalation (vapor, gas, mg/L/day)		< 1	1 - 2.5	> 2.5 - 20	> 20
Inhalation (dust/mist/fume, mg/L/day)		< 0.1	0.1 - 0.5	> 0.5 - 5	> 5
Developmental Toxicity		High	Moderate	Low	Very Low
Oral (mg/kg/day)		< 50	50 - 250	> 250	> 1000
Dermal (mg/kg/day)		< 100	100 - 500	> 500	> 2000
Inhalation (vapor, gas, mg/L/day)		< 1	1 - 2.5	> 2.5	> 20
Inhalation (dust/mist/fume, mg/L/day)		< 0.1	0.1 - 0.5	> 0.5	> 5
Neurotoxicity (90-day study)		High	Moderate	Low	
Oral (mg/kg-bw/day)		< 10	10 - 100	> 100	
Dermal (mg/kg-bw/day)		< 20	20 - 200	> 200	
Inhalation (vapor/gas) (mg/L/6h/day)		< 0.2	0.2 - 1.0	> 1.0	
Inhalation (dust/mist/fume) (mg/L/6h/day)		< 0.02	0.02 - 0.2	> 0.2	
Repeated Dose Toxicity (90-day study)		High	Moderate	Low	
Oral (mg/kg-bw/day)		< 10	10 - 100	> 100	
Dermal (mg/kg-bw/day)		< 20	20 - 200	> 200	
Inhalation (vapor/gas) (mg/L/6h/day)		< 0.2	0.2 - 1.0	> 1.0	
Inhalation (dust/mist/fume) (mg/L/6h/day)		< 0.02	0.02 - 0.2	> 0.2	
Sensitization		High	Moderate	Low	
Skin sensitization		High frequency of sensitization in humans and/or high potency in animals (GHS Category 1A)	Low to moderate frequency of sensitization in human and/or low to moderate potency in animals (GHS Category 1B)	Adequate data available and not GHS Category 1A or 1B	
Respiratory Sensitization		Occurrence in humans or evidence of sensitization in humans based on animal or other tests (equivalent to GHS Category 1A and 1B)	Limited evidence including the presence of structural alerts	Adequate data available indicating lack of respiratory sensitization	
Irritation/Corrosivity	Very High	High	Moderate	Low	Very Low
Eye Irritation/Corrosivity	Irritation persists for > 21 days or corrosive	Clearing in 8-21 days, severely irritating	Clearing in 7 days or less, moderately irritating	Clearing in less than 24 hrs, mildly irritating	Not irritating
Skin Irritation/Corrosivity	Corrosive	Severe irritation at 72 hours	Moderate irritation at 72 hours	Mild or slight irritation at 72 hours	Not irritating
Endocrine Activity	For this endpoint, High/Moderate/Low etc. characterizations will not apply. Evidence will be summarized in a narrative.				
Environmental Toxicity and Fate					
Aquatic Toxicity	Very High	High	Moderate	Low	
Acute Aquatic Toxicity (LC50 or EC50) (mg/L)	< 1.0	1 - 10	> 10 - 100	> 100	
Chronic Aquatic Toxicity (LOEC) (mg/L)	< 0.1	0.1 - 1	> 1 - 10	> 10	
Environmental Persistence	Very High	High	Moderate	Low	Very Low
Persistence in water, soil or sediment	Half-life > 180 days or recalcitrant	Half life of 60 – 180 days	Half-life < 60 but ≥ 16 days	Half-life < 16 days OR passes Ready Biodegradability test not including the 10-day window.	Passes Ready Biodegradability test with 10-day window.
Persistence in air (half-life days)	For this endpoint, High/Moderate/Low etc. characterizations will not apply. A qualitative assessment of available data will be prepared.				
Bioaccumulation (BAF / BCF)	Very High	High	Moderate	Low	
BCF/BAF	> 5,000	5,000 – 1,000	<1,000 – 100	< 100	
Log BCF/BAF	>3.7	3.7-3	<3-2	<2	

3D Printing and Materials Online Survey



This survey is intended to assist in research aimed to assess the sustainability of 3D printing materials. The goal of this survey is to discover how materials and processes are evaluated and implemented in the 3D printing industry. The results will feed into a tool that introduces designers to materials that are sustainable while communicating the impact and trade-offs of material choices during the design process.

1. What industry does your company belong to?

2. What is your role in the company?

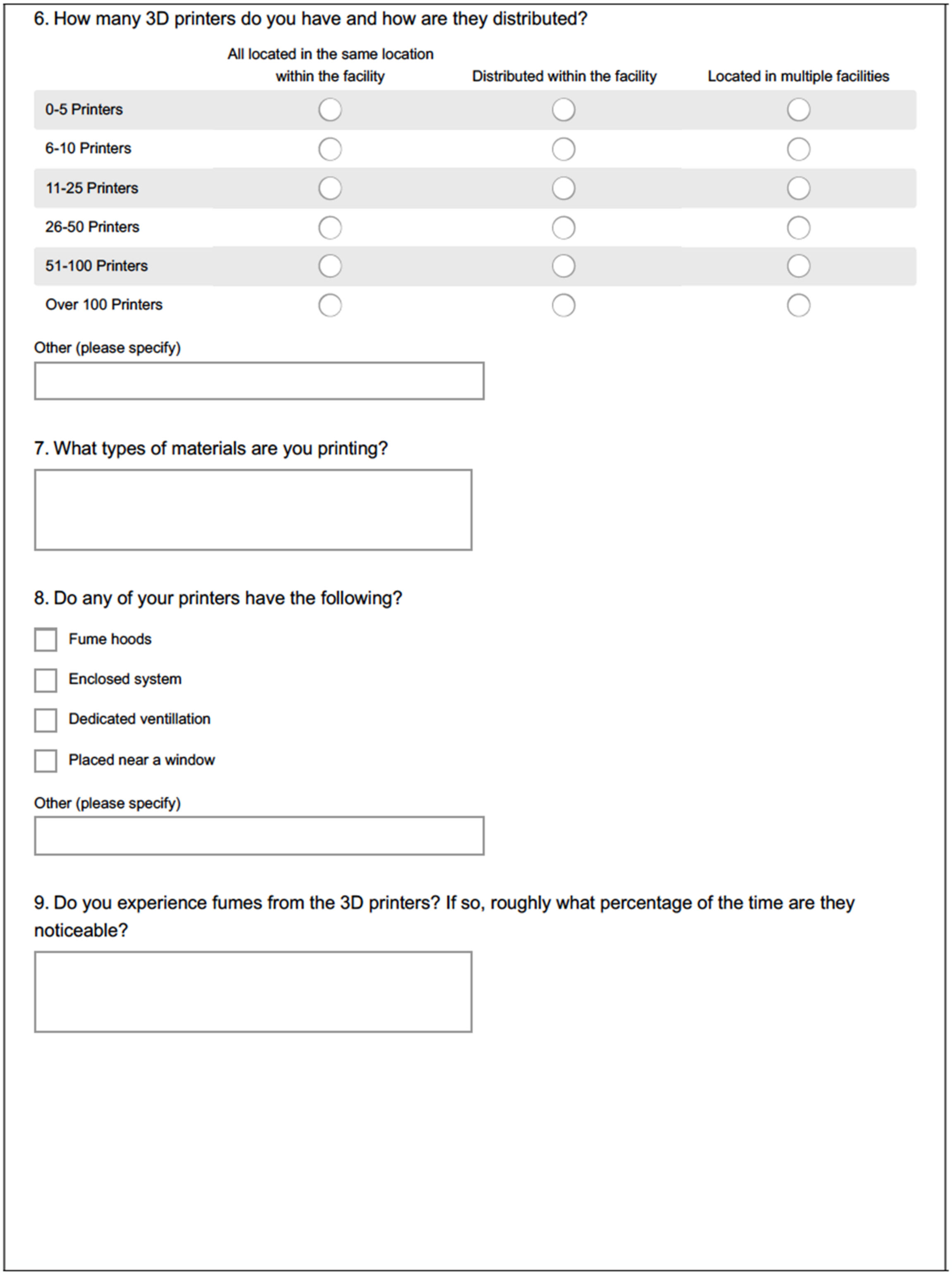
3. What 3D printer technology do you use? Please check all that apply.

☐ Fused Deposition Modeling (FDM)
☐ Selective Laser Sintering (SLS)
☐ Stereolithography (SLA)

Other (please specify)

4. Why did you choose these printer technologies?

5. What kinds of products do you print (e.g., prototypes for students, consumer products for the sports market)?



6. How many 3D printers do you have and how are they distributed?

	All located in the same location within the facility	Distributed within the facility	Located in multiple facilities
0-5 Printers	○	○	○
6-10 Printers	○	○	○
11-25 Printers	○	○	○
26-50 Printers	○	○	○
51-100 Printers	○	○	○
Over 100 Printers	○	○	○

Other (please specify)

7. What types of materials are you printing?

8. Do any of your printers have the following?

☐ Fume hoods

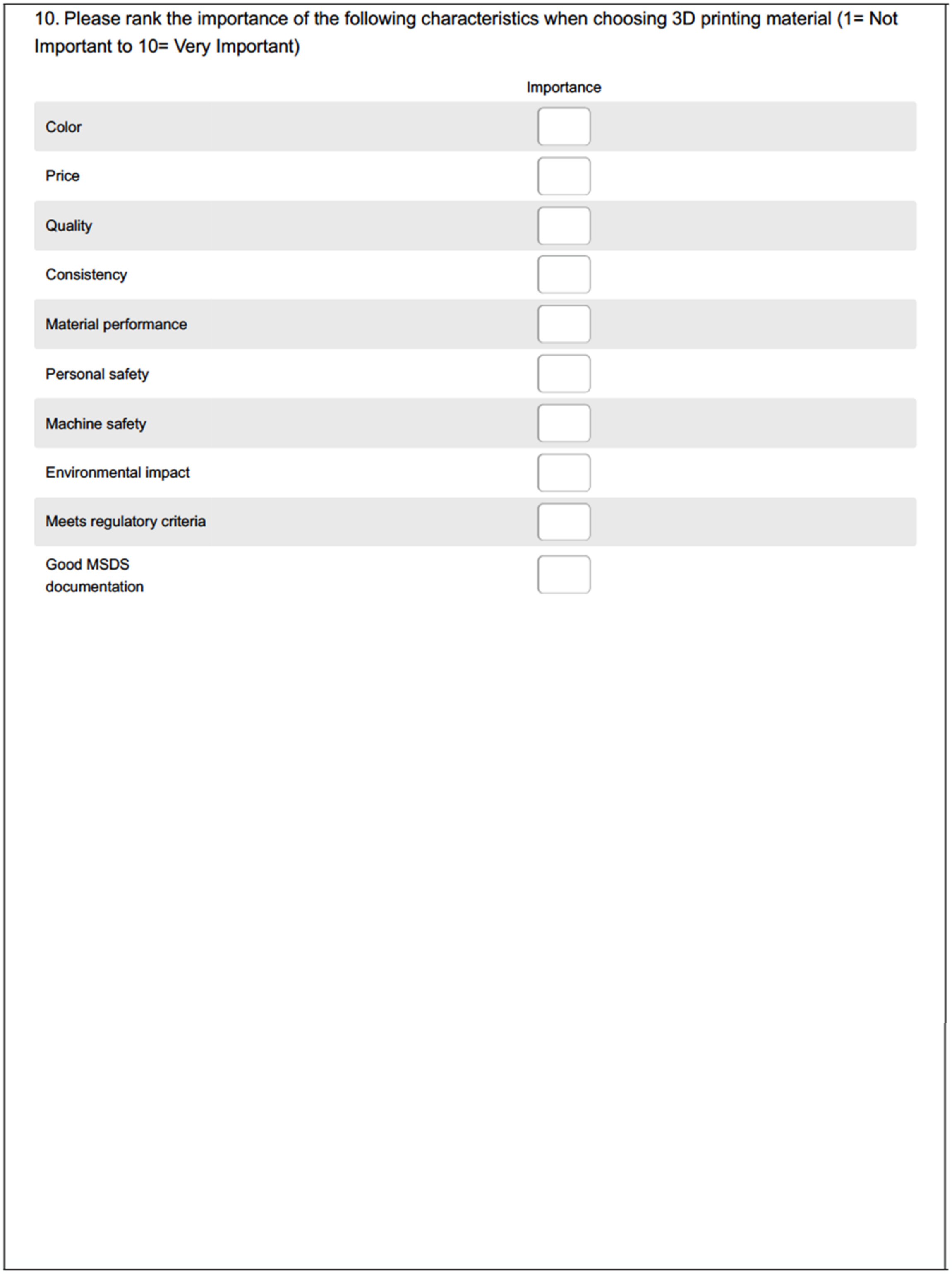
☐ Enclosed system

☐ Dedicated ventillation

☐ Placed near a window

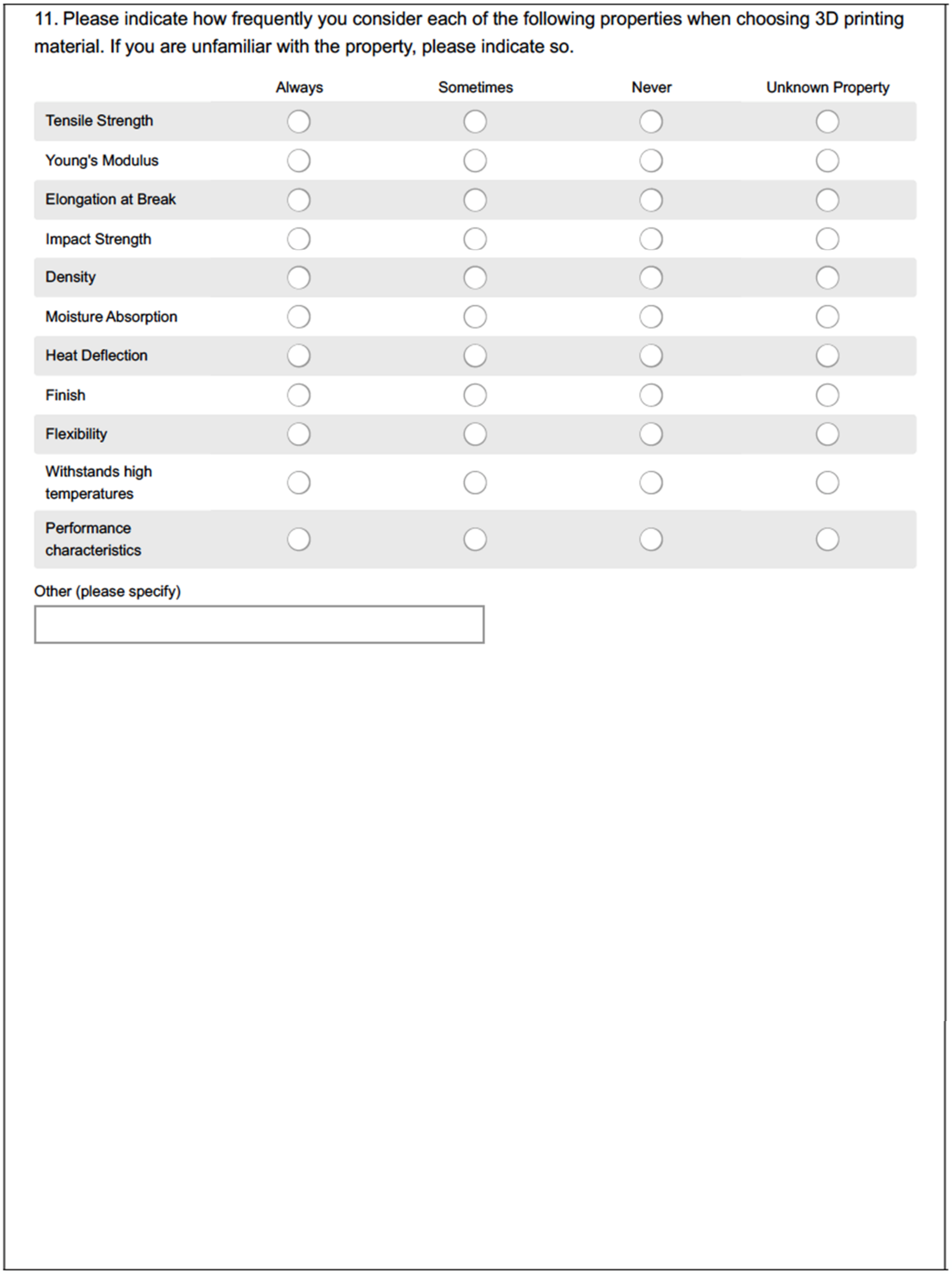
Other (please specify)

9. Do you experience fumes from the 3D printers? If so, roughly what percentage of the time are they noticeable?



10. Please rank the importance of the following characteristics when choosing 3D printing material (1= Not Important to 10= Very Important)

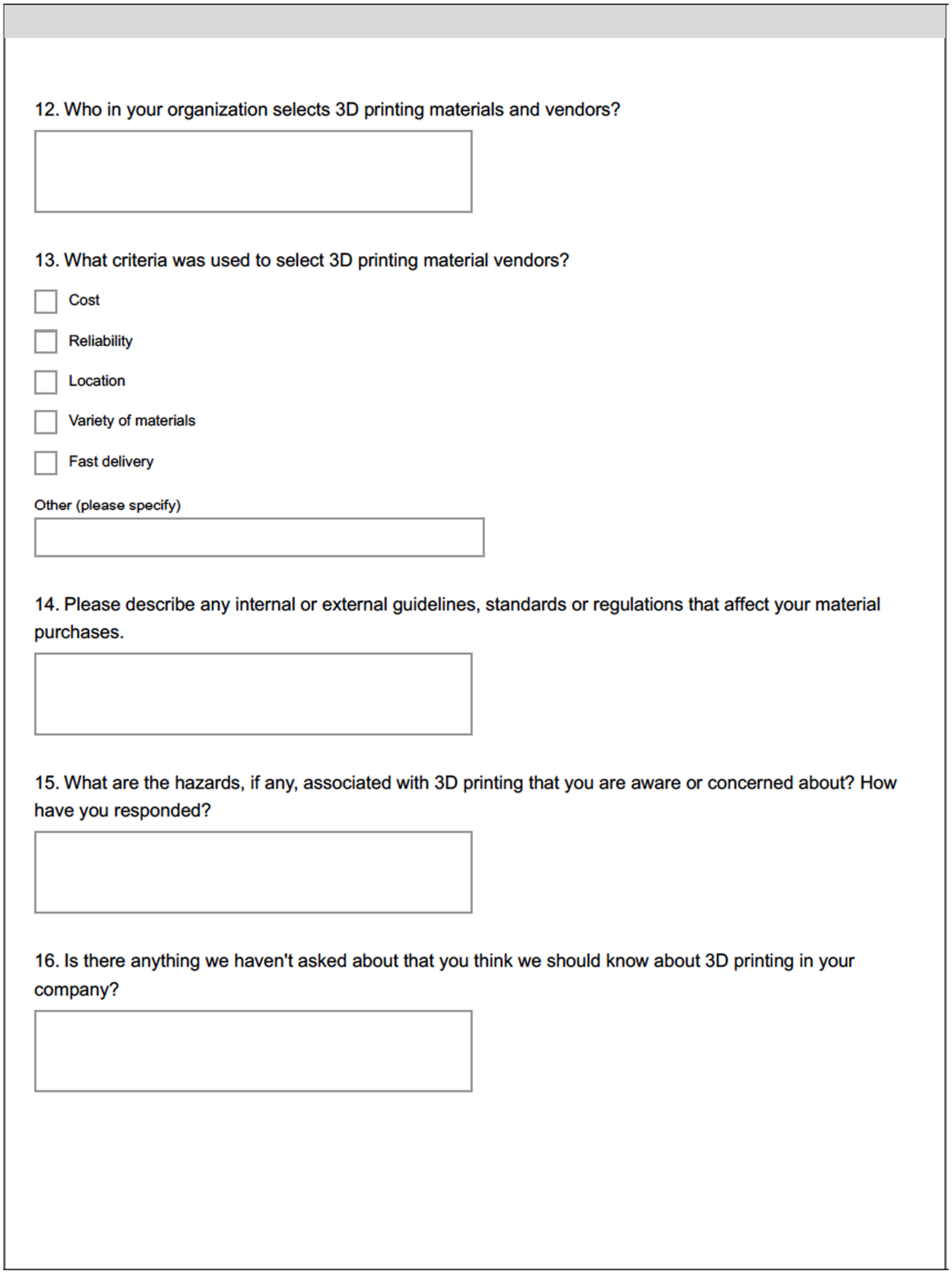
	Importance
Color	
Price	
Quality	
Consistency	
Material performance	
Personal safety	
Machine safety	
Environmental impact	
Meets regulatory criteria	
Good MSDS documentation	



11. Please indicate how frequently you consider each of the following properties when choosing 3D printing material. If you are unfamiliar with the property, please indicate so.

	Always	Sometimes	Never	Unknown Property
Tensile Strength	○	○	○	○
Young's Modulus	○	○	○	○
Elongation at Break	○	○	○	○
Impact Strength	○	○	○	○
Density	○	○	○	○
Moisture Absorption	○	○	○	○
Heat Deflection	○	○	○	○
Finish	○	○	○	○
Flexibility	○	○	○	○
Withstands high temperatures	○	○	○	○
Performance characteristics	○	○	○	○

Other (please specify)



12. Who in your organization selects 3D printing materials and vendors?

13. What criteria was used to select 3D printing material vendors?

☐ Cost

☐ Reliability

☐ Location

☐ Variety of materials

☐ Fast delivery

Other (please specify)

14. Please describe any internal or external guidelines, standards or regulations that affect your material purchases.

15. What are the hazards, if any, associated with 3D printing that you are aware or concerned about? How have you responded?

16. Is there anything we haven't asked about that you think we should know about 3D printing in your company?

A.5 Chapter 5

The material presented below is available online from the sources referenced. It is included here to have a thorough representation of this body of research material in one place.

Process Chemistry Material Type

Process Chemistry Type	Definition	Example	Known and Potential Residual
Reactant	A chemical that reacts to form another chemical that is not a polymer. Formerly feedstocks and intermediates.	Chlorine is a reactant to make chloroprene.	No
Monomer	A chemical that reacts to form a polymer	Vinyl chloride is a monomer of polyvinyl chloride	No
Catalyst (homogeneous/ unstructured unknown)	Substance that increases the rate of a reaction without being consumed. Usually used in small amounts relative to the reactants. Homogeneous catalysts are generally more difficult to separate from a reaction	Sodium hydroxide is a catalyst when making bio-diesel	Yes
Catalyst (heterogeneous/ structured)	Substance that increases the rate of a reaction without being consumed. Usually used in small amounts relative to the reactants. Heterogeneous/structured catalysts are a different phase from the reactants and designed to be separated from their reaction. These would therefore be less likely to be present at relevant levels in the final product.	Supported Nickel is a catalyst for hydrogenated soybean oil	No
Additive - non-reactive	Chemical that is added to provide specific characteristics to the final compounds and remains in the form in which it was added	Phthalate plasticizers are non-reactive additives to soften plastics	Yes
Additive - reactive	Chemical that is added to a compound and reacts with another additive to produce a different compound.	TBBPA is a reactive additive in printed circuit boards	No
Byproduct	Substance generated from production that is not useful to production of the target material and that is used in other processes or managed as waste or released into the work environment or released to the outdoor environment.	Glycerol is a byproduct of making bio-diesel from vegetable oil	Yes
Pollutant/Contaminant	Unintentional and unwanted substance that comes mixed with the target material. May originate from contaminants to the original feedstock or as a byproduct of the chemical processes that are used to create the material.	2,4-dichlorophenol is a pollutant/contaminant for Triclosan	Yes
Unknown role	A chemical whose role is unknown.		No

Process aid	Chemical added to provide specific characteristics during manufacturing	Lead is used as a process aid in PVC processing	Yes
Product of a reversible reaction	Chemicals that reappear because they are part of a reversible reaction / equilibrium process.	Formaldehyde released from urea/phenol formaldehyde resin	Yes
Solvent	Liquid (usually) used to dissolve chemicals and facilitate a reaction. Also present as the 'fluid' in fluid applied products	Benzene is a solvent for polyethylene	No
Component	An often desirable chemical present in a mixture that does not undergo reaction. Like a contaminant but makes up a larger fraction of the mixture.	benzene is a component of petroleum distillates	Yes
Initiator	A chemical used to initiate a chain reaction, common in polymerizations	Hydrogen peroxide is an initiator for polytetrafluoroethylene	No

All of these chemicals create potential exposure issues for the workers and to neighboring communities (if emitted). The reactants, monomers, structured catalysts, reactive additives, solvents, and initiators generally do not end up in products so are not an exposure concern for users. Unstructured catalysts, byproducts, contaminants, process aids, products of reversible reactions, and components sometimes end up in products, usually in trace amounts. Non reactive additives are frequently intended to end up in products in amounts that range from trace to very large percentages.

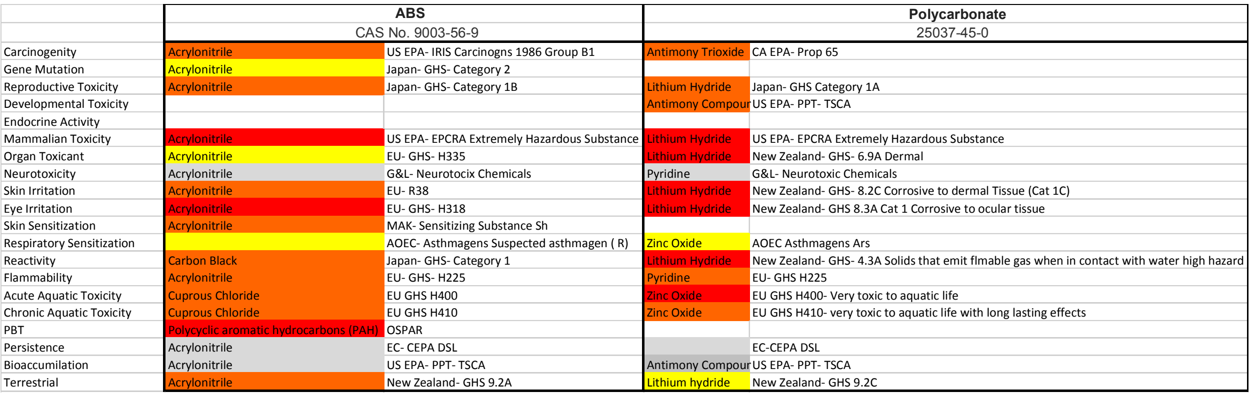
Lifecycle Frequency: a substance's use or creation in the manufacturing process is characterized by how common it is. The frequency determines if the hazard is included in the Manufacturing Hazard dot.

Frequency	**Definition**	**Included in Manufacturing Hazard dot?**
Unknown	No known use in manufacturing or unclear.	No
Occasional/Rare	A substance that is only infrequently used – found in less than one third of the manufacturing processes references researched.	No
Frequent	a substance that is commonly used - associated with at least one third of the manufacturing process references researched	Yes
Integral	A substance that is necessarily inherent to the manufacture of this material and without which it would be a different material or for which no alternatives have been demonstrated.	Yes

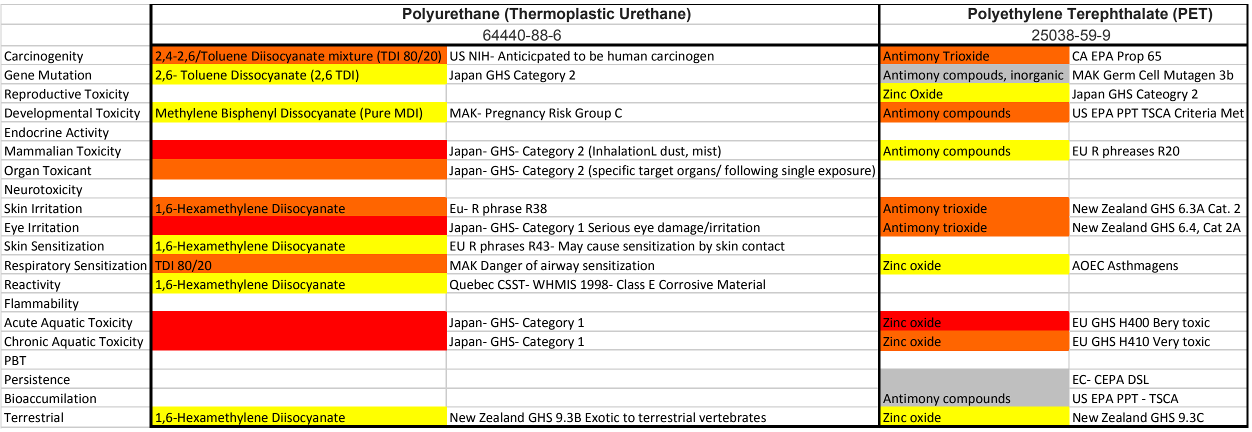
Known Residual

Known residuals are chemicals from any source that testing consistently shows are residuals in another chemical. This is indicated by the word “(known)” in the frequency column of the process chemistry table. The hazards of known residuals are incorporated into the Residual Hazards dot.

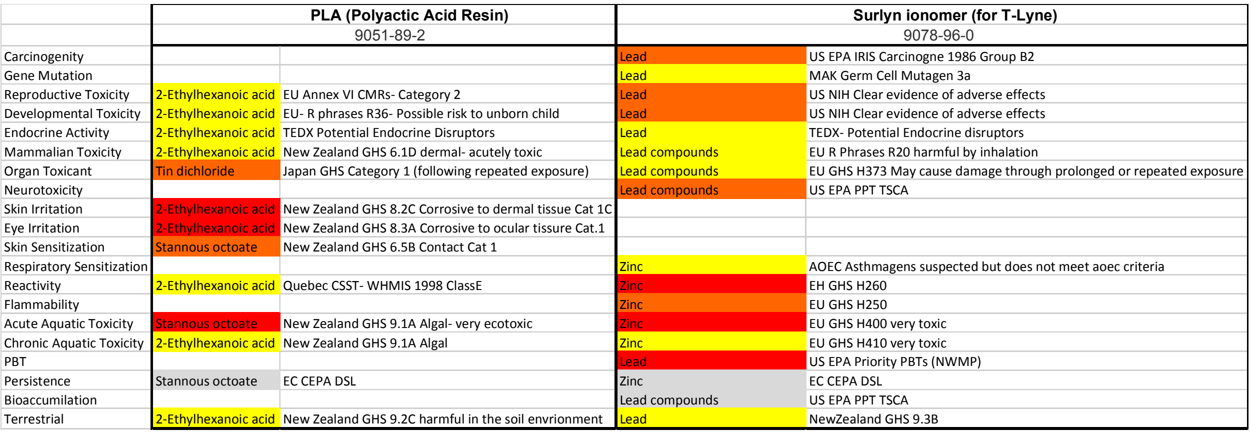
Hazard Data Collected on 3D Printing Material from The Pharos Project [163]



	ABS		Polycarbonate	
	CAS No. 9003-56-9		25037-45-0	
Carcinogenity	Acrylonitrile	US EPA- IRIS Carcinogns 1986 Group B1	Antimony Trioxide	CA EPA- Prop 65
Gene Mutation	Acrylonitrile	Japan- GHS- Category 2		
Reproductive Toxicity	Acrylonitrile	Japan- GHS- Category 1B	Lithium Hydride	Japan- GHS Category 1A
Developmental Toxicity			Antimony Compour	US EPA- PPT- TSCA
Endocrine Activity				
Mammalian Toxicity	Acrylonitrile	US EPA- EPCRA Extremely Hazardous Substance	Lithium Hydride	US EPA- EPCRA Extremely Hazardous Substance
Organ Toxicant	Acrylonitrile	EU- GHS- H335	Lithium Hydride	New Zealand- GHS- 6.9A Dermal
Neurotoxicity	Acrylonitrile	G&L- Neurotocix Chemicals	Pyridine	G&L- Neurotoxic Chemicals
Skin Irritation	Acrylonitrile	EU- R38	Lithium Hydride	New Zealand- GHS- 8.2C Corrosive to dermal Tissue (Cat 1C)
Eye Irritation	Acrylonitrile	EU- GHS- H318	Lithium Hydride	New Zealand- GHS 8.3A Cat 1 Corrosive to ocular tissue
Skin Sensitization	Acrylonitrile	MAK- Sensitizing Substance Sh		
Respiratory Sensitization		AOEC- Asthmagens Suspected asthmagen (R)	Zinc Oxide	AOEC Asthmagens Ars
Reactivity	Carbon Black	Japan- GHS- Category 1	Lithium Hydride	New Zealand- GHS- 4.3A Solids that emit flmable gas when in contact with water high hazard
Flammability	Acrylonitrile	EU- GHS- H225	Pyridine	EU- GHS H225
Acute Aquatic Toxicity	Cuprous Chloride	EU GHS H400	Zinc Oxide	EU GHS H400- Very toxic to aquatic life
Chronic Aquatic Toxicity	Cuprous Chloride	EU GHS H410	Zinc Oxide	EU GHS H410- very toxic to aquatic life with long lasting effects
PBT	Polycyclic aromatic hydrocarbons (PAH)	OSPAR		
Persistence	Acrylonitrile	EC- CEPA DSL		EC-CEPA DSL
Bioaccumilation	Acrylonitrile	US EPA- PPT- TSCA	Antimony Compour	US EPA- PPT- TSCA
Terrestrial	Acrylonitrile	New Zealand- GHS 9.2A	Lithium hydride	New Zealand- GHS 9.2C



	Polyurethane (Thermoplastic Urethane)		Polyethylene Terephthalate (PET)	
	64440-88-6		25038-59-9	
Carcinogenity	2,4-2,6/Toluene Diisocyanate mixture (TDI 80/20)	US NIH- Anticicpated to be human carcinogen	Antimony Trioxide	CA EPA Prop 65
Gene Mutation	2,6- Toluene Dissocyanate (2,6 TDI)	Japan GHS Category 2	Antimony compouds, inorganic	MAK Germ Cell Mutagen 3b
Reproductive Toxicity			Zinc Oxide	Japan GHS Cateogry 2
Developmental Toxicity	Methylene Bisphenyl Dissocyanate (Pure MDI)	MAK- Pregnancy Risk Group C	Antimony compounds	US EPA PPT TSCA Criteria Met
Endocrine Activity				
Mammalian Toxicity		Japan- GHS- Category 2 (InhalationL dust, mist)	Antimony compounds	EU R phreases R20
Organ Toxicant		Japan- GHS- Category 2 (specific target organs/ following single exposure)		
Neurotoxicity				
Skin Irritation	1,6-Hexamethylene Diisocyanate	Eu- R phrase R38	Antimony trioxide	New Zealand GHS 6.3A Cat. 2
Eye Irritation		Japan- GHS- Category 1 Serious eye damage/irritation	Antimony trioxide	New Zealand GHS 6.4, Cat 2A
Skin Sensitization	1,6-Hexamethylene Diisocyanate	EU R phrases R43- May cause sensitization by skin contact		
Respiratory Sensitization	TDI 80/20	MAK Danger of airway sensitization	Zinc oxide	AOEC Asthmagens
Reactivity	1,6-Hexamethylene Diisocyanate	Quebec CSST- WHMIS 1998- Class E Corrosive Material		
Flammability				
Acute Aquatic Toxicity		Japan- GHS- Category 1	Zinc oxide	EU GHS H400 Bery toxic
Chronic Aquatic Toxicity		Japan- GHS- Category 1	Zinc oxide	EU GHS H410 Very toxic
PBT				
Persistence				EC- CEPA DSL
Bioaccumilation			Antimony compounds	US EPA PPT - TSCA
Terrestrial	1,6-Hexamethylene Diisocyanate	New Zealand GHS 9.3B Exotic to terrestrial vertebrates	Zinc oxide	New Zealand GHS 9.3C



	PLA (Polyactic Acid Resin)		Surlyn ionomer (for T-Lyne)	
	9051-89-2		9078-96-0	
Carcinogenity			Lead	US EPA IRIS Carcinogne 1986 Group B2
Gene Mutation			Lead	MAK Germ Cell Mutagen 3a
Reproductive Toxicity	2-Ethylhexanoic acid	EU Annex VI CMRs- Category 2	Lead	US NIH Clear evidence of adverse effects
Developmental Toxicity	2-Ethylhexanoic acid	EU- R phrases R36- Possible risk to unborn child	Lead	US NIH Clear evidence of adverse effects
Endocrine Activity	2-Ethylhexanoic acid	TEDX Potential Endocrine Disruptors	Lead	TEDX- Potential Endocrine disruptors
Mammalian Toxicity	2-Ethylhexanoic acid	New Zealand GHS 6.1D dermal- acutely toxic	Lead compounds	EU R Phrases R20 harmful by inhalation
Organ Toxicant	Tin dichloride	Japan GHS Category 1 (following repeated exposure)	Lead compounds	EU GHS H373 May cause damage through prolonged or repeated exposure
Neurotoxicity			Lead compounds	US EPA PPT TSCA
Skin Irritation	2-Ethylhexanoic acid	New Zealand GHS 8.2C Corrosive to dermal tissue Cat 1C		
Eye Irritation	2-Ethylhexanoic acid	New Zealand GHS 8.3A Corrosive to ocular tissure Cat.1		
Skin Sensitization	Stannous octoate	New Zealand GHS 6.5B Contact Cat 1		
Respiratory Sensitization			Zinc	AOEC Asthmagens suspected but does not meet aoec criteria
Reactivity	2-Ethylhexanoic acid	Quebec CSST- WHMIS 1998 ClassE	Zinc	EH GHS H260
Flammability			Zinc	EU GHS H250
Acute Aquatic Toxicity	Stannous octoate	New Zealand GHS 9.1A Algal- very ecotoxic	Zinc	EU GHS H400 very toxic
Chronic Aquatic Toxicity	2-Ethylhexanoic acid	New Zealand GHS 9.1A Algal	Zinc	EU GHS H410 very toxic
PBT			Lead	US EPA Priority PBTs (NWMP)
Persistence	Stannous octoate	EC CEPA DSL	Zinc	EC CEPA DSL
Bioaccumilation			Lead compounds	US EPA PPT TSCA
Terrestrial	2-Ethylhexanoic acid	New Zealand GHS 9.2C harmful in the soil envrionment	Lead	NewZealand GHS 9.3B

	Polystyrene		PVA (Polyvinyl acetate)	
	9003-53-6		9003-20-7	
Carcinogenity	▨	IARC Group 3- Agent is not classifiable as to its carcinogencity to human	▨	IARC Group 3- Agent is not classifiable as to its carcinogenicity to humans
Gene Mutation	Styrene	Zew Zealand- GHS- 6.6B Suspected human mutagens		
Reproductive Toxicity				
Developmental Toxicity	Styrene	EU_ GHS H361d- Suspected of damaging the unborn child	Hydrogen peroxide	MAK Pregnancy Risk Group C
Endocrine Activity	Styrene	EU Priority Endocrine Disrupters Category 1		
Mammalian Toxicity	Styrene	EU R phrases R20- Harmful by inhalation	Hydrogen peroxide	US EPA EPCRA Extremely hazardous substance
Organ Toxicant	Styrene	EU GHS H372 Causes damange through prolonged or repeated exposure	Hydrogen peroxide	Japan- GHS Category 1 following single exposure
Neurotoxicity	Styrene	G&L- Neurotoxic chemicals		
Skin Irritation	Styrene	EU R phrases R38- Irritating to skin	Hydrogen peroxide	EU GHS H314 causes severe skin burns and eye damage
Eye Irritation	Styrene	EU GHS H319 Causes serious eye irritation	Hydrogen peroxide	Japan GHS- Category 1 Sereious eye damage/irritation
Skin Sensitization				
Respiratory Sensitization	Styrene	AOEC Asthmagens		
Reactivity			Hydrogen peroxide	EU GHS H271 May cause fire or explosion, strong oxidiser
Flammability	Ethylbenzene	EU GHS H225- Highly flammable liquid and vapor		
Acute Aquatic Toxicity	Styrene	New Zealand GHS 9.1A Algal very ecotoxic		
Chronic Aquatic Toxicity	Styrene	New Zealand- GHS 9.1B (Crustacean) very exotoxic		
PBT				
Persistence	▨	EC- CEPA DSL	▨	EC- CEPA DSL
Bioaccumilation	Styrene	US EPA- PPT- TScA- Low bioaccumulation potential		
Terrestrial	Styrene	New Zealand GHS 9.3B Exotoxic to terrestrial vertebrates		

	Bronze		Copper	
	12597-70-5		7440-50-8	
Carcinogenity	Lead	US EPA IRIS Carcinogens 1986 Group B2, probable human carcinogen	▨	US EPA 1986 Group D- Not classifiable as to human carcinogenicity
Gene Mutation	Lead	MAK 3a		
Reproductive Toxicity	Lead	US NIH		
Developmental Toxicity	Lead	US NIH		
Endocrine Activity	Lead	Potential Endocrine Disruptors TEDX		
Mammalian Toxicity	Lead Compounds	EU Rphrases R20- harmful by inhalation (gas or vapor or dust/mist)	🟥	US EPA-OPP_Registred Pesticides
Organ Toxicant	Lead Compounds	Eu GHS H373- May cause damage to organs through prolonged or repeated exposure		
Neurotoxicity	Lead Compounds	US EPA PPT, TSCA Criteria met		
Skin Irritation				
Eye Irritation				
Skin Sensitization				
Respiratory Sensitization	Zinc	AOEC Asthamagens Sustmected but does not meet criteria		
Reactivity	Zinc	EU GHS H260- In contact with water releases flammable gasses which may ignite spontaneously		
Flammability	Zinc	EU GHS H250- Catches fire spontaneously if exposed to air		
Acute Aquatic Toxicity	Lead Compounds	EU GHS H400- Very toxic to aquatic life		
Chronic Aquatic Toxicity	Lead Compounds	Eu R phrases R53- May cause long term adverse effects in the aquatic environment		
PBT	Lead	US EPA NWMP		
Persistence	Copper	EC CEPA DSL	▨	EC CEPA DSL
Bioaccumilation	Lead compounds	US EPA PPT chemical action plans, tsca cirteira met		
Terrestrial	Lead	New Zealand- GHS- 9.3B Ecotoxic to terrestrial vertebrates		

	PETG		Styrene	
	25640-14-6		100-42-5	
Carcinogenity			🟧	US NIH Reasonably anticipated to be
Gene Mutation			🟨	New Zealand- GHS- 6.6B- Suspected human mutagens
Reproductive Toxicity			Ethylbenzene	Japan GHS Toxic to reproduction Category 1B
Developmental Toxicity			🟨	EU GHS H361d Suspected of damaging unborn child
Endocrine Activity			🟨	EU Priority endocrine disruptors category 1
Mammalian Toxicity			🟨	EU R phrases R20- Harmful by inhalation
Organ Toxicant			🟧	EU GHS H372- Causes damage through prolonged or repeated exposure
Neurotoxicity			▨	G&L Neurotoxic Chemical
Skin Irritation			🟧	EU R phrases R38- Irritating to skin
Eye Irritation	1,4-Cyclohexanedimethanol	Australia- GHS- H318 Causes serious eye damage	🟧	EU GHS H319- causes serious eye irritaiton
Skin Sensitization				
Respiratory Sensitization			🟧	OEC Asthmagen
Reactivity				
Flammability			🟨	EU GHS H226- Flammable liquid and vapor
Acute Aquatic Toxicity	2-(4,6-Diphenyl-1,3,5-Triazin-2-YL)-5-((Hexyl)oxy)-Phenol	New Zeland- GHS- 9.1D (algal) Slighlty harmful	🟥	New Zealand GHS 9.1A algal- very ecotoxic
Chronic Aquatic Toxicity	2-(4,6-Diphenyl-1,3,5-Triazin-2-YL)-5-((Hexyl)oxy)-Phenol	EU R Phrases- R53- May caus long term adverse effect	🟧	New Zealand GHS 9.1B (crustacean) very ecotoxic
PBT				
Persistence			▨	US EPA PPT- TSCA
Bioaccumilation			▨	US EPA- PPT- TSCA
Terrestrial			🟨	New Zealand GHS 9.3B Ecotoxic

	Nylon 6		Nylon 6.6		TPE (Thermoplastic Elastom	HIPS		Iron		Brass
	25038-54-4		32131-17-2		308079-71-2	9003-55-8		7439-89-6		12597-71-6
Carcinogenity	▨	IARC Group 3			No hazard data reported on Pharos	▨	IARC Group 3			No hazard data reported on Pharos
Gene Mutation										
Reproductive Toxicity										
Developmental Toxicity										
Endocrine Activity										
Mammalian Toxicity	🟥 Nitrogen	US EPA OPP								
Organ Toxicant										
Neurotoxicity										
Skin Irritation										
Eye Irritation										
Skin Sensitization										
Respiratory Sensitization										
Reactivity										
Flammability										
Acute Aquatic Toxicity										
Chronic Aquatic Toxicity										
PBT										
Persistence	▨	EC- CEPA DSL	▨	EC- CEPA DSL		▨	EC CEPA DSL	▨	EC- CEPA DSL	
Bioaccumilation										
Terrestrial										

Where, the hazards level are indicated by the following

🟥	Very High
🟧	High
🟨	Moderate
🟩	Low
▨	Potential Concern
☐	Data not Available

A.6 Chapter 6

The material presented below is available online from the sources referenced. It is included here to have a thorough representation of this body of research material in one place.

3D Printing Material Database: Information on description, mechanical properties and printing guidelines that appear in the tool. The information was collected from material manufacturers and MatterHacker material supplier [150], [154]–[158]

Material	Price [$/kg]	Printing Temperature [C]	Melting Temperature [C]	Tg Glass Transition Temperature [C]	Print Bed Temperature [C]	Printing Speed [mm/s]
Taulman Alloy 910	84	250-255	210	82	30-65	Data Unavailable
Taulman Guidel!ne	42	244-252	220	77	68-68	Data Unavailable
Taulman Nylon 680	164	250-255	210	93	30-65	Data Unavailable
Taulman T-Glase	76	235-242	217	77	68-68	Data Unavailable
Taulman 645 Nylon	76	250-255	217	52	30-65	Data Unavailable
Taulman TECH-G	36	235-242	217	77	68-68	Data Unavailable
Taulman PCTPE	84	235-242	203	74	50-50	Data Unavailable
Taulman T-Lyne	80	185-242	110	Data Unavailable	60-60	Data Unavailable
Taluman Nylon Bridge	18	250-255	217	52	30-65	Data Unavailable
Taulman BluPrint	33	265-275	255	100	90-90	Data Unavailable
Taulman Nylon 230	55	228-235	195	68	24-24	Data Unavailable
Taulman 618 Nylon	58	245-245	218	48	30-65	Data Unavailable
SemiFlex from NinjaFlex	55	225-235	216	35	Data Unavailable	10-20
NinjaTek NinjaFlex TPE	110	225-235	216	35	Data Unavailable	10-20
PolyMaker PolyPlus PLA	67	195-230	Data Unavailable	60	Data Unavailable	40-90
PolyMaker PolyFlex	27	220-235	Data Unavailable	Data Unavailable	Data Unavailable	30-90
PolyMaker PC Max	47	250-270	Data Unavailable	113	80	30-90
ColorFabb PLA/PHA	55	195-220	155	55	50-60	40-100
ColorFabb Wood Fill	108	195-220	155	55	50-60	40-100
ColorFabb Bamboo Fill	108	210-230	155	55	50-60	40-60
ColorFabb CorkFill	37	210-230	155	Data Unavailable	50-60	40-60
ColorFabb Bronze Fill	100	195-220	150	55	50-60	40-100
ColorFabb CopperFill	104	190-210	150	Data Unavailable	50-60	40-100
ColorFabb SteelFill	51	190-210	150	Data Unavailable	50-60	40-80
ColorFabb XT CF20 Carbon	104	240-260	100	75	60-70	40-70
ColorFabb XT	73	Data Unavailable	245	75	70-70	30-60
ColorFabb nGen	44	210-240	100	Data Unavailable	60-60	30-100
Proto-Pasta Polycarbonate ABS	70	275-285	Data Unavailable	Data Unavailable	120-120	Data Unavailable
ABS Filament	29	230-240	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable
Pro Series ABS	42	230-240	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable
Pro Series PLA	42	185-205	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable
ColorFabb BrassFill	87	195-220	Data Unavailable	Data Unavailable	50-60	40-100
HIPS	39	220-230	Data Unavailable	Data Unavailable	50-110	Data Unavailable
Laybrick	144	185-215	Data Unavailable	Data Unavailable	24-60	Data Unavailable
Laywood	136	175-230	Data Unavailable	Data Unavailable	24-60	Data Unavailable
Bendlay	152	215-240	Data Unavailable	Data Unavailable	24-50	Data Unavailable

Material	Density [g/cm3]	Ultimate Tensile Strength [MPa]	Yield Tensile Strength [MPa]	Young's Modulus [MPa]	Ultimate Elongation [%]
Taulman Alloy 910	Data Unavailable	Data Unavailable	56	503	32
Taulman Guidel!ne	Data Unavailable	Data Unavailable	47	1941	5.9
Taulman Nylon 680	Data Unavailable	Data Unavailable	48	Data Unavailable	34
Taulman T-Glase	1.2767	32.5	41	440	3
Taulman 645 Nylon	Data Unavailable	Data Unavailable	36	213	186
Taulman TECH-G	Data Unavailable	Data Unavailable	41	440	3
Taulman PCTPE	Data Unavailable	Data Unavailable	35	73	498
Taulman T-Lyne	Data Unavailable	Data Unavailable	31	490	300
Taluman Nylon Bridge	1.1277	Data Unavailable	33	183	248.2
Taulman BluPrint	Data Unavailable	Data Unavailable	46	365	18
Taulman Nylon 230	Data Unavailable	Data Unavailable	34	73	417
Taulman 618 Nylon	Data Unavailable	31.6	32	153	86
SemiFlex from NinjaFlex	1.2216	25.5	4	12	660
NinjaTek NinjaFlex TPE	1.1869	25.5	4	12	660
PolyMaker PolyPlus PLA	1.2	Data Unavailable	47	2636 ± 330	1.9
PolyMaker PolyFlex	1.2	Data Unavailable	29	Data Unavailable	330.1
PolyMaker PC Max	1.19	49.08	60	2048	12.24
ColorFabb PLA/PHA	1.24	61.5	Data Unavailable	2960	Data Unavailable
ColorFabb Wood Fill	1.15	46	Data Unavailable	3290	Data Unavailable
ColorFabb Bamboo Fill	1.19	46	Data Unavailable	3300	Data Unavailable
ColorFabb CorkFill	1.18	40	Data Unavailable	2	Data Unavailable
ColorFabb Bronze Fill	3.9	30	Data Unavailable	Data Unavailable	5 to 10
ColorFabb CopperFill	4	25	Data Unavailable	Data Unavailable	3 to 10
ColorFabb SteelFill	3.13	23	Data Unavailable	Data Unavailable	1 to 3
ColorFabb XT CF20 Carbon	1.35	76	Data Unavailable	Data Unavailable	7.5
ColorFabb XT	1.27	28	50	1900	110
ColorFabb nGen	1.2	35	50	1800	193
Proto-Pasta Polycarbonate ABS	1.27	Data Unavailable	52	Data Unavailable	100
ABS Filament	1.07	29	Data Unavailable	Data Unavailable	Data Unavailable
Pro Series ABS	1.07	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable
Pro Series PLA	1.25	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable
ColorFabb BrassFill	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable
HIPS	1.028	21	Data Unavailable	Data Unavailable	50
Laybrick	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable
Laywood	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable
Bendlay	Data Unavailable	Data Unavailable	Data Unavailable	Data Unavailable	175

Material	FDA	UL94HB	UL94V2	Color	Description
Taulman Alloy 910	Yes	Yes	Yes	Natural	
Taulman Guidel!ne	Yes	None	None	Natural	
Taulman Nylon 680	Yes	Yes	Yes	Natural	Medical Grade, Low Temperature Print
Taulman T-Glase	Yes	None	None	Natural	Low Temperature Print
Taulman 645 Nylon	None	Yes	Yes	Natural, Nlack	
Taulman TECH-G	Yes	None	None	Natural	
Taulman PCTPE	None	Yes	Yes	Natural	Flexible, Bendable,
Taulman T-Lyne	Yes	None	None	Transparent	Durable,Transparent, Flexible, Moldable, Wide range of temperatures
Taluman Nylon Bridge	None	Yes	Yes	Natural	
Taulman BluPrint	Yes	None	Yes	Natural	Handles high heat deflection
Taulman Nylon 230	None	Yes	Yes	Natural	Chemical resistant, no heated bed
Taulman 618 Nylon	None	Yes	Yes	Natural	Durable, Chemical resistant, (to alcohols, resins +MEK, oils, acetone, alkaline)
SemiFlex from NinjaFlex	None	None	None	Transparent	Abrasion resistant, Chemical resistant, Flexible
NinjaTek NinjaFlex TPE	None	None	None	Black, White, Almond, Semi-Transparent, Silver, Sky Blue, Sapphire Blue, Red, Green	Abrasion resistant, Chemical resistant, Flexible,Durable, Bendable
PolyMaker PolyPlus PLA	Yes	None	None	White, Black, Natural, Orange, Yellow, Blue, Red, Teal, Green, Grey, Purple	
PolyMaker PolyFlex	None	None	None	White	Flexible
PolyMaker PC Max	None	None	None	White, Black	
ColorFabb PLA/PHA	None	None	None	Black, blue grey, blue, red, white, yellow, silver, gold, orange, natural, brown	No Warp
ColorFabb Wood Fill	None	None	None	Wood	
ColorFabb Bamboo Fill	None	None	None	Bamboo	
ColorFabb CorkFill	None	None	None	Cork	
ColorFabb Bronze Fill	None	None	None	Bronze	
ColorFabb CopperFill	None	None	None	Copper	
ColorFabb SteelFill	None	None	None	Steel	
ColorFabb XT CF20 Carbon	None	None	None	Black	Stiff
ColorFabb XT	Yes	None	None	Black, Dark grey, trasnparent, red, white, purple, orange, green,	Temperature resistant, Styrene free
ColorFabb nGen	Yes	None	None	Black, Dark Grey, Clear	Temperature resistant, Styrene free
Proto-Pasta Polycarbonate ABS	None	None	None	Black	
ABS Filament				Black, White, Nautral, Gold, Silver, Grey, Blue, Purple, Pink, Magenta, Red, Orange, Yellow, Green, Brown	Temperature resistant, strong, Flexible
Pro Series ABS	None			Black, Wite, Natural, Silver, Blue, Purple, Red, Organe, Yellow, Green, Brown, Teal, Burgundy	Durable, Flexible
Pro Series PLA	None			Aqua, Red, Green, Yellow, Burgundy, Grey, Purple, Blue, Translucent, Black, Brown, White, Orange, Pink	
ColorFabb BrassFill	Data Unavailable				
HIPS	Data Unavailable			Black, Pink, Green, Yellow, Clear	Brittle
Laybrick	Data Unavailable				Brittle, near zero warping, high interlayer adhesion
Laywood	Data Unavailable			Cherry, Pine	
Bendlay	Yes				Medical Grade, No stress whitening, Slight to no warping

VBA Code for Tool

Launching the User Form

```
Sub Initialize()
UserForm1.Show
With UserForm1.ColorBox
   .AddItem "Black"
   .AddItem "White"
   .AddItem "Natural"
   .AddItem "Red"
   .AddItem "Blue"
   .AddItem "Green"
   .AddItem "Orange"
   .AddItem "Yellow"
   .AddItem "Purple"
   .AddItem "Brown"
   .AddItem "Silver"
   .AddItem "Gold"
   .AddItem "Pink"
End With
End Sub
```

Clearing Sheets

```
Sub ClearSheet2()
Sheets("Sheet2").Select
   Cells.Select
   Selection.ClearContents
   Range("A1").Select
End Sub

Sub ClearSheet3()
Sheets("Sheet3").Select
   Range("A2:Q52").Select
   Selection.ClearContents
   ActiveWindow.SmallScroll Down:=-10
   Range("A2").Select
End Sub

Sub Macro21()
Sheets("SustainabilityResults").Select
   Cells.Select
   Selection.ClearContents
   Range("B2").Select
End Sub
```

```
Sub Macro2()
Sheets("PerformanceResults").Select
   Range("A2:V40").Select
   Selection.ClearContents
   Range("A2").Select
End Sub
```

Start Query Search

```
Sub StartQuerySearch()
Range("H20").Select
   Sheets("Performance").Select
   Range("A2:V37").Select ‘boundaries of data
   Selection.Copy
   Sheets("Variables1").Select
   Cells.Select
   Range("B10").Activate
   Application.CutCopyMode = False
   Selection.ClearContents
   Range("A1").Select
   Sheets("Performance
").Select
   Selection.Copy
   Sheets("Variables1").Select
   ActiveSheet.Paste
   Range("F8").Select
End Sub
```

Body of Code

```
Function FindMatches(C) As String
StartQuerySearch

numRows = 37 'number of materials
Count = 0
Dim Criteria As String
Dim CriteriaName As String

SheetActive = "Variables1"
NextActive = "Variables2"
Sheets(NextActive).Cells.ClearContents

For i = 2 To C
   Criteria = Sheets("Sheet2").Cells(i, 1).Value
   CriteriaName = Sheets("Sheet2").Cells(i, 2).Value
   tala = GetSearch(CriteriaName)
   CriteriaType = CStr(tala(1))
   Col = tala(2)
```

```
  For j = 1 To numRows
      If compare(Sheets(SheetActive).Cells(j, Col).Value, Criteria, CriteriaType) = "Yes" Then
      Count = Count + 1
      For k = 1 To 22 'Number of Columns
         Sheets(NextActive).Cells(Count, k).Value = Sheets(SheetActive).Cells(j, k).Value
      Next k
    End If
  Next j

  numRows = Count
  Count = 0
  tempo = SheetActive
  SheetActive = NextActive
  NextActive = tempo
  Sheets(NextActive).Cells.ClearContents

Next i
FindMatches = SheetActive
MsgBox ("Search Complete")

Sheets("PerformanceResults").Range("A2:B32").Value =
Sheets(SheetActive).Range("A1:B31").Value
Sheets("PerformanceResults").Range("D2:E32").Value =
Sheets(SheetActive).Range("E1:F31").Value
Sheets("PerformanceResults").Range("H2:S32").Value =
Sheets(SheetActive).Range("K1:V31").Value

For k = 1 To 37
Sheets("PerformanceResults").Cells(k + 1, 3).Value = Sheets(SheetActive).Cells(k, 3).Value &
"-" & Sheets(SheetActive).Cells(k, 4).Value
Sheets("PerformanceResults").Cells(k + 1, 6).Value = Sheets(SheetActive).Cells(k, 7).Value &
"-" & Sheets(SheetActive).Cells(k, 8).Value
Sheets("PerformanceResults").Cells(k + 1, 7).Value = Sheets(SheetActive).Cells(k, 9).Value &
"-" & Sheets(SheetActive).Cells(k, 10).Value
Next k

For k = 2 To 37
If Sheets("PerformanceResults").Cells(k, 3).Value = "Data Unavailable-Data Unavailable" Then
Sheets("PerformanceResults").Cells(k, 3).Value = "Data Unavailable"
End If

If Sheets("PerformanceResults").Cells(k, 6).Value = "Data Unavailable-Data Unavailable" Then
Sheets("PerformanceResults").Cells(k, 6).Value = "Data Unavailable"
End If
```

```
If Sheets("PerformanceResults").Cells(k, 7).Value = "Data Unavailable-Data Unavailable" Then
Sheets("PerformanceResults").Cells(k, 7).Value = "Data Unavailable"
End If

If Sheets("PerformanceResults").Cells(k, 3).Value = "-" Then
Sheets("PerformanceResults").Cells(k, 3).ClearContents
End If

If Sheets("PerformanceResults").Cells(k, 6).Value = "-" Then
Sheets("PerformanceResults").Cells(k, 6).ClearContents
End If

If Sheets("PerformanceResults").Cells(k, 7).Value = "-" Then
Sheets("PerformanceResults").Cells(k, 7).ClearContents
End If
Next k

For i = 2 To 37
r = 2
For Z = 2 To 37
If Sheets("PerformanceResults").Cells(Z, 1).Value = Sheets("Sustainability").Cells(i, 1).Value
Then
Sheets("SustainabilityResults").Rows(r).EntireRow.Value =
Sheets("Sustainability").Rows(i).EntireRow.Value
End If
r = r + 1
Next Z
Next i

Sheets("SustainabilityResults").Rows(1).EntireRow.Value =
Sheets("Sustainability").Rows(1).EntireRow.Value

Sheets("Performance").Visible = False
Sheets("Sheet2").Visible = False
Sheets("Sheet3").Visible = False
Sheets("Variables1").Visible = False
Sheets("Variables2").Visible = False
Sheets("Sustainability").Visible = False

Sheets("SustainabilityResults").Activate
Range("A16") = "Thermal decomposition and degradation of filament leads to hazardous
products."
Range("A16").Font.Color = vbRed
Range("A17") = "General Exposure Controls:"
Range("A18") = "Please follow the Safety Sheets provided by the material supplier."
Range("A19") = "Always provide adequate ventilation while printing."
```

```
Range("A20") = "The use of respiratory protection is recommended when dust has formed.
Particle filter type P1 or FFP1 are recommended."
Range("A21") = "Extrusion of plastic filaments are extremely hot and may cause burns. Heat
protection gloves and safety glasses are recommended."
Range("A16:A21").Font.Bold = True

Range("B1").Activate
Sheets("PerformanceResults").Activate
End Function

Function compare(Have As String, Want As String, CT) As String
If (CT = "S") Then
   If LookForIn(Want, Have) = "True" Then
   compare = "Yes"
   Else
   compare = "No"
   End If
ElseIf (CT = "LT" And IsNumeric(Have) = True) Then
   If Val(Have) <= Val(Want) Then
   compare = "Yes"
   Else
   compare = "No"
   End If
ElseIf (CT = "GT") Then
   If Val(Have) >= Val(Want) Then
   compare = "Yes"
   Else
   compare = "No"
   End If
Else
   compare = "No"
End If
End Function

Function LookForIn(str1 As String, str2 As String) As String
Dim vArr1
Dim vArr2
Dim vTest
Dim lngCnt As Long
vArr1 = Split(Replace(str1, " ", vbNullString), ",")
vArr2 = Split(Replace(str2, " ", vbNullString), ",")
On Error GoTo strExit

For lngCnt = LBound(vArr1) To UBound(vArr1)
vTest = Application.Match(vArr1(lngCnt), vArr2, 0)
If Not IsError(vTest) Then LookForIn = LookForIn & vArr1(lngCnt) & ", "
```

```
Next lngCnt
If Len(LookForIn) > 0 Then
LookForIn = Left$(LookForIn, Len(LookForIn) - 2)
Else
strExit:
LookForIn = "No Matches"
End If

If LookForIn = "No Matches" Then
   LookForIn = "False"
Else
   LookForIn = "True"
End If
End Function

Function GetSearch(Criteria As String) As Variant
Dim arr(2) As Variant
For i = 1 To 22 'Number of columns
   If (Sheets("Hidden").Cells(2, i).Value = Criteria) Then
      arr(1) = Sheets("Hidden").Cells(3, i).Value
      arr(2) = Sheets("Hidden").Cells(1, i).Value
   End If
Next i
GetSearch = arr
End Function
```

Fixing Results Format

```
Sub MacroPrintT()
Sheets("PerformanceResults").Select
   ActiveCell.Offset(0, 1).Range("A1").Select
   ActiveCell.FormulaR1C1 = "=Variables2!R[-1]C&""-""&Variables2!R[-1]C[1]"
   ActiveCell.Select
   Selection.AutoFill Destination:=ActiveCell.Range("A1:A29"), Type:= _
      xlFillDefault
   ActiveCell.Range("A1:A29").Select
   ActiveCell.Select
End Sub

Sub MacroBedT()
Sheets("PerformanceResults").Select
   ActiveCell.Offset(0, 3).Range("A1").Select
   ActiveCell.FormulaR1C1 = "=Variables2!R[-1]C[1]&""-""&Variables2!R[-1]C[2]"
   ActiveCell.Select
   Selection.AutoFill Destination:=ActiveCell.Range("A1:A29"), Type:= _
      xlFillDefault
   ActiveCell.Range("A1:A29").Select
```

```
    ActiveCell.Select
End Sub

Sub MacroSpeed()
Sheets("PerformanceResults").Select
    ActiveCell.Offset(0, 1).Range("A1").Select
    ActiveCell.FormulaR1C1 = "=Variables2!R[-1]C[2]&""-""&Variables2!R[-1]C[3]"
    ActiveCell.Select
    Selection.AutoFill Destination:=ActiveCell.Range("A1:A29"), Type:= _
        xlFillDefault
    ActiveCell.Range("A1:A29").Select
    ActiveCell.Select
End Sub
```

A.7 Chapter 7

No content.