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Designing a Recycled Material Database (RMD)

Development of a Material Database to Inspire Product Designers and
CMF Designers to Use Recycled Materials in the Project at Hand

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TABLE OF CONTENTS

LIST OF FIGURES.....	5
ABSTRACT (ENGLISH).....	8
ABSTRACT (ITALIAN).....	9
Introduction.....	10
Chapter 1 Background and Topics - Recycled Material.....	12
1.1 From Waste to Recycled Material	12
1.2 Study Topics and Research Path Design.....	17
Chapter 2 Recycled Material in Product Design	19
2.1 Recycled Material Cases Study	19
2.2 Methodology.....	19
2.3 Results and Discussion of the Case Study Analysis	20
2.3.1 Recycled material classification and answer for Q1.....	20
2.3.2 Waste-based organic material	23
2.3.3 Waste-based polymer	28
2.3.4 Waste-based metal and other inorganic material	37
2.3.5 Waste-based composite.....	39
2.3.6 Analysis of the potential of recycled materials in product design and answer for Q2	44
Chapter 3 Material Selection Study in Product Design.....	49
3.1 Product Material Selection Study in Academic Context	49
3.1.1 Study background and purpose	49
3.1.2 Material selection for product design (Ashby & Johnson, 2013)	50
3.1.3 Material in product selection (MiPS) (Kesteren, 2008)	53
3.1.4 Meaning driven material selection (Karana, 2009)	56
3.1.5 Material driven design (MDD) (Karana et al., 2015)	60
3.1.6 Summary.....	62
3.2 Material Selection Study in CMF Discipline	65
3.2.1 Study background: Material consideration in CMF design	65
3.2.2 Study content and purpose.....	67
3.2.3 CMF design process and main activities	67
3.2.4 Material considerations in the CMF design process	70
3.2.5 Typology of CMF elements related to materials	75
3.2.6 Summary.....	77
Chapter 4 Recycled material database design	78
4.1 The reason for building a recycled material database	78
4.2 Idea of Database.....	78

4.3 Basic framework and content introduction of the database.....	80
4.4 Database Content	83
4.4.1 Part 1: Recycled material knowledge base	83
4.4.2 Part 2: Material Exploration Module	90
4.4.3 Part 3: Downloading Centre.....	96
Chapter 5 Discussion and Conclusion.....	97
Reference.....	99
Appendices.....	106
Acknowledgements.....	108

LIST OF FIGURES

Figure 1 Linear production system (Prezi, 2013).....	12
Figure 2 Waste hierarchy.....	13
Figure 3 Recyclable solid waste material (RSWM)	15
Figure 4 Important aspects considered for RSWM recycling	16
Figure 5 Total MSW Generated by Material vs. Total MSW Recycling by Material (2018,USA)..	16
Figure 6 Google Pixel 5 case made by fabric from old PET bottle.....	17
Figure 7 Research path design	18
Figure 8 Recycled material case data statistics	21
Figure 9 Recycled material classification design based on applications in product design and material composition.....	22
Figure 10 Waste-based organic material case study.....	24
Figure 11 Three plant-based fiber making process (Coconut water / Orange peels / Pineapple leaves)	26
Figure 12 Natural plant based material for panel developed by Organoid, Heat press process and final sample(Left), From natural waste to natural pattern (Right).....	27
Figure 13 Material exploration from animal waste in slaughterhouses by Clemence Grouin-Rigaux.....	28
Figure 14 Waste-based synthetic polymer material case study	29
Figure 15 Atlantic deck chair designed and manufactured by Govaplast (Left), Govaplast Product Series (Right)	31
Figure 16 Acoustic lighting by recycled PET felt (Left, Impact Acoustic) and felt shaping process (Right, Refelt)	32
Figure 17 Raytent yarn making process (Left), material applications in rug (Right).....	33
Figure 18 Plastic stone tiles by ENIS AKIEV (Left), polyurethane foam dust furniture by Charlotte Kidger (Right)	34
Figure 19 Waste-based bio-polymer material case study.....	35
Figure 20 Bio-thermoplastic from potato waste (Left, Chip[s] Board), eyewear made by Parblex® bioplastic (Right)	37
Figure 21 Waste-based metal and other inorganic material case study.....	38
Figure 22 Aviation aluminum waste (Left), bio-Luminum tiles for wall treatment by Coverings ETC (Right).....	39
Figure 23 Waste-based composite material case study.....	40
Figure 24 Marble waste collection (Left), Stonethica used for interior design (Right).....	41
Figure 25 Material exploration samples(Left), knife sharpening whetstone with three sharpening level by Steven Akoun (Right)	42
Figure 26 Huguet X Apt, experimental terrazzo for furniture	42
Figure 27 DENIMX uprecycling process of jean waste (Left), Motorcycle exterior design by DENIMX (Right)	43
Figure 28 Corktex carpet (Left), Lisboa acoustically absorptive composite cork wall system by Lars Beller Fjetland (Right)	43
Figure 29 Manufacturing Process and Application Analysis - Materials from Case Study.....	44
Figure 30 Blowing experiment samples (Left), final product, an emotional night lamp (Right).	48

Figure 31 Pre-conditions influencing material selection (Prendeville, 2014)	49
Figure 32 Overview of existing resources for material selection (Veelaert, 2016)	50
Figure 33 Products, Materials and Processes database (Granta 2016)	52
Figure 34 Information classification about product design (Ashby, 2013)	53
Figure 35 Different tools presentation in MiPS technique, 1-5 are performed in the definition step,	55
Figure 36 Sexy materials selected by 12 female and 12 male participants (left), Sensorial scales (right)	57
Figure 37 The meanings of Materials Model (above), Visualisation of modest based on The Meanings of Materials Model (below) (Karana, 2009)	58
Figure 38 One of the interface of this tool: quantitative evaluation of the sensorial scales page. Three sensorial properties of materials that contribute to the meaning of sexy are identified: smooth, not elastic, and glossy.	59
Figure 39 MDD method framework and application case (Karana et al., 2015)	61
Figure 40 Relationship between aesthetic attributes and physical attributes (Ashby & Johnson, 2013)	63
Figure 41 Sensorial parameters attributing meanings to materials (Karana, 2010)	63
Figure 42 Product material selection study in academic context	64
Figure 43 Oppo R11 - FC Barcelona Limited Edition, CMF design innovation	65
Figure 44 Schematic diagram of CMFPSE theoretical model (Li, 2019)	66
Figure 45 'the burning metal project' by hamanishi DESIGN (Left), milling of the Suzuri Series of table and bench seats by Alex Rasmussen, Neal Feay (Right)	66
Figure 46 Study result of CMF process and main activities	69
Figure 47 Material selection study in the CMF design process	71
Figure 48 C/M/F indicator and material attributes in CMF design (Becerra, 2016)	72
Figure 49 Basic characteristics of CMF material (Li, 2009)	73
Figure 50 Fig 3.17 The cross image on the left is trend forecasting of Chinese design styles in 2021-2022 by Yang Design,	74
Figure 51 CMF material information chart — taking material - douglas fit as an example	76
Figure 52 Framework of recycled materials database	82
Figure 53 Material-Attribute Board	84
Figure 54 Material-Process Board	85
Figure 55 Material-Experiment Board	86
Figure 56 Material-Product Board	87
Figure 57 Material-Pros Board	87
Figure 58 Material-Trend Board (material from food waste in product&service trend insight). ..	88
Figure 59 Color element-oriented material information display mode (This display mode could map the current material color information (HSB) to Parctical Color Coordinate. Designers can visually view the colors of different materials and provide inspiration for material color design)	88
Figure 60 Material knowledge base access interface design and function introduction	89
Figure 61 Material exploration module interface composition	91
Figure 62 "Match button" function	92
Figure 63 "Add label" function — personal databse creation	93

Figure 64 Material exploration module use status based on a hytophetical project 95

ABSTRACT (ENGLISH)

Nowadays, various sectors of society are committed to thinking about how to cope with waste in high-level utilization to relieve resource crisis, environmental burden. According to the waste hierarchy and current practice, upcycling waste to obtain value-added materials or products is considered an admirable waste treatment method. Under the idea of circular economy, we can identify two types of recycling routes (closed-loop recycling, open-loop recycling) according to whether the recycled material is put into the original use track or form new materials or products. The interest of this thesis revolves around the novel materials from waste and creative products made from them. Considering that it is still a relatively fresh and explorative material for designers working in the field of traditional industrial design, this thesis extensively examines the characteristics of such materials and their application potential in the field of product design. Following works are implemented: Material case studies retrieved from online repositories; analysis of existing material selection methods and database to obtain the designer's motivations and requirements for product selection. Finally, based on the above two insights, this thesis describes the framing and design of the Recycled Material Database (RMD). It is highly interactive, designers could access knowledge about recycled material applications in product design. Simultaneously, it also contains a built-in material exploration tool, combined with the functions of visual board creation and image matching from design appeals to assist designers to acquire design inspirations with the recycled materials surrounding the project at hand, encourage them to actively invest, and put them into product creation practice.

Keywords: waste, recycled material, product design, material selection, Color Material Finishing (CMF), material database, design tool

ABSTRACT (ITALIAN)

Attualmente vari settori della società sono impegnati a pensare a come affrontare lo spreco dei rifiuti sfruttandolo ad un alto livello per alleviare la crisi delle risorse e il peso sull'ambiente. Secondo la gerarchia dei rifiuti e la pratica attuale, il riciclaggio realizzato a partire dai rifiuti per ottenere determinati materiali o prodotti a valore aggiunto è considerato un metodo di trattamento dei rifiuti ammirevole. Nell'idea di economia circolare, possiamo identificare due tipi di percorsi di riciclaggio (riciclaggio a ciclo chiuso, riciclaggio a ciclo aperto) a seconda che il materiale riciclato venga reinserito nella traccia di utilizzo originale o formi nuovi materiali o prodotti. L'interesse di questa tesi ruota attorno ai nuovi materiali provenienti da rifiuti e attorno ai prodotti creativi realizzati a partire da essi, dando loro un fascino di design unico e un'apprezzabile qualità sostenibile. Considerando che per i designer il fatto di lavorare nel campo del design industriale tradizionale è ancora una strada relativamente fresca ed esplorativa, questa tesi conduce un'analisi sulle caratteristiche di tali materiali e sulla loro applicazione nel campo del design del prodotto. Ciò implica i seguenti lavori: casi studio su materiali recuperati da archivi online; analisi dei metodi e dei database esistenti di selezione dei materiali per ottenere la motivazione del progettista e i requisiti per la selezione del prodotto. Infine, sulla base delle due intuizioni di cui sopra, questa tesi descrive l'inquadratura e la progettazione del Database dei Materiali Riciclati (RMD). È altamente interattivo, i designer possono accedere alle conoscenze sulle applicazioni dei materiali riciclati nella progettazione del prodotto. Allo stesso tempo, contiene anche uno strumento di esplorazione dei materiali integrato, combinato con le funzioni di creazione di pannelli visivi e immagini che corrispondono a estetiche di design per aiutare i designer ad acquisire ispirazioni di design con i materiali riciclati attorno a cui ruotano i loro progetti, in modo da incoraggiarli a investire attivamente su di essi e metterli nella pratica di creazione del prodotto.

Parole chiave: rifiuti, materiale riciclato, design del prodotto, selezione dei materiali, finitura del materiale a colori (CMF), database dei materiali, strumento di progettazione.

Introduction

Waste management organizations, industrial groups, environmentalists, and designers are working together to think about how to deal with waste in high-level utilization to relieve resource crisis, environmental burden. The waste hierarchy, as a tool for evaluating the process of protecting the environment and resource and energy consumption, indicates that prevention is the primary way to reduce waste, followed by reuse, recycling, recovery, and disposal. For the waste stream, a widely accepted method is recycling. In the field of design, many designers and material developers reuse or recycle waste and apply them to creative material/product design. Related achievements we can see, such as new material recovered from waste: Polyplank – a kind of composite (made of recovered thermoplastic polymers and cellulosic fibers from wood) which has better strength and durability than plastic as a home guardrail. Material based on waste has certain advantages and potentials compared to traditional materials. Product designers should consider this type of material which can contribute to products in functional, aesthetic, and environmentally friendly three aspects simultaneously.

It is certain that nowadays, more and more material developers and progressive designers are exploring various materials from waste and applying them to product design, which has both design appeal and excellent sustainable qualities. However, there are still many obstacles for the average designer to introduce recycled materials into the projects at hand as an alternative to the original materials, such as the lack of integrated information on the characteristics, functional aspects, and product application potential of recycled materials, which makes most designers believe that these materials only have advantages in terms of sustainability. However, a shallow examination of materials in this field confirms that recycled materials have not only green qualities but also a wide range of other advantages and potential. It is necessary to conduct in-depth research to explore what it brings to product design and encourage more designers to acquire related knowledge and try to apply them to the projects at hand.

The study can be divided into the following sections:

Chapter 1 firstly sets out the background of the study, discusses the waste hierarchy, recycling activities, considers two ways of recycling waste materials, and thus leads to the scope of the material group discussed in this paper — recycled material. At the end of the chapter, a three-step research path is presented, defining the goal of the study: proposing a recycled materials database for product designers to better encourage designers to use this type of material in the project at hand.

In chapter 2, case studies are conducted to examine the properties of recycled materials and their potential for use in product design in the following industries: housewares, architecture and interiors, packaging and disposable products, textiles, furniture, etc. Making a classification for recycled materials. Material potential analysis based on their properties, pros, and cons presented in various applications.

Chapter 3 studies the material selection activities for product designers to determine what material information is important to them, what form of material selection interaction is conducive to inspire their project, and which parts can be used as references for the design of the recycled materials database.

In chapter 4, a database that focuses on presenting information about recycled materials is designed based on the knowledge of chapters 2 and 3, and loaded with a built-in design tool to assist designers to find design opportunities with recycled materials based on the project at hand. Finally, discuss and summarize the database design, reveal its limitations and deficiencies, and put forward suggestions for future development.

Chapter 1 Background and Topics - Recycled Material

1.1 From Waste to Recycled Material

In the current predominantly linear production systems¹, waste generation is inevitable (Prezi, 2013). The rapid growth of the middle class with the main idea of taking products as well-being stimulates a large number of purchases which means myriad of resources consumed while corresponding to the more demanding resource extraction cycle and the continuous accumulation of waste. According to United Nations statistics, the global material footprint² increased from 43 billion tons in 2000 to 92 billion tons in 2017, an increase of 20% year on year. In 2017, the per capita materials consumption in the world was 12 tons per year, among which the per capita materials consumption in high-income countries was as high as 26 tons (United Nations Statistics Division, 2019). Our use of resources has resulted in more and more solid waste being discarded or incinerated. Waste is becoming a large problem, as we are running out of land for landfilling, and end-of-life waste treatment has negative environmental and health impacts. This is especially a problem for emerging economies, where material use (and hence discarding of it) is growing very rapidly, while limited waste management infrastructure exists (Worrell & Reuter, 2014, p. 5)

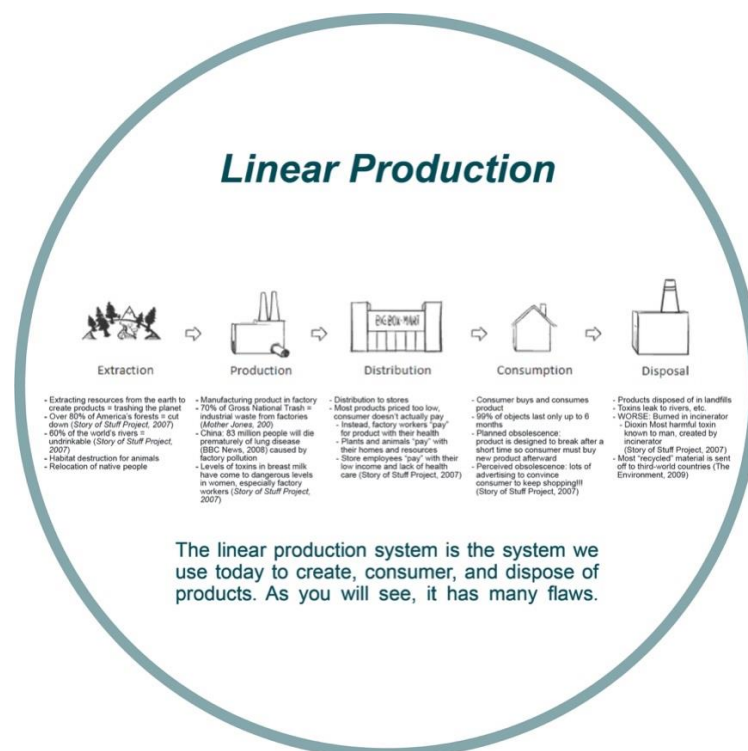


Figure 1 Linear production system (Prezi, 2013)

The waste management sectors, and related practitioners are committed to solving waste

¹ The linear production system is the system we use today to create, consumer, and dispose of products (Prezi, 2013)

² "Material footprint" refers to the total amount of raw materials extracted to meet final consumption demands.

problems to avoid resource crises and a huge burden on the environment. It is known that the waste hierarchy is adopted by many countries and organizations to establish policies to guide the waste sector (EC, 2008). The waste hierarchy, a tool used in the evaluation of processes that protects the environment alongside resource and energy consumption from most favorable to least favorable actions (Hansen et al., 2002), first initiated by the politician Ad Lansink in the Dutch parliament in 1979 (Watson, 2013). After continuous revision, it was determined to enter European legislation in 2008 as the five levels from the top to the bottom, are prevention (reducing waste at the source), preparing for re-use (using materials repeatedly), recycling (make recovered material enter use-stream), recovery (recovering energy from waste), disposal (safe disposal of waste to landfill) (EC, 2008). Among them, waste prevention is the most advantageous option, followed by preparation for reuse, recycling, and other recovery methods, while waste disposal is the most unfavorable (Figure 2). Nowadays, recycling is considered to be the most acceptable way to extract value from the waste stream. It is reported that as of 2016 in Europe, the recycling rates of the four main waste streams (municipal waste, packaging waste, waste electrical and electronic equipment, waste excluding major mineral waste) were 46%, 67.1%, 41.2%, and 57.3% respectively, an increase of 20% year on year compared to 2010 (EEA, 2020). By effectively recycling these wastes, more recovered materials are used for secondary materials or composting, which means that the environmental impact of landfills is reduced to a certain extent.



Figure 2 Waste hierarchy

Waste streams are flows of specific waste, from its source through to recycling, recovery, or disposal (European Parliament [EP], 2015). According to material lifecycle characteristics, some wastes are generated in the manufacturing process (can be considered as post-industrial waste or pre-consumer waste³), while others are generated at the end of life (can be considered as post-consumer waste⁴) (Ragaert, 2017; Wesam, 2016). An officially defined

³ Post-industrial waste or pre-consumer waste is commonly used in manufacturing industries and is often not considered recycling in the traditional sense. Examples: Shavings, sawdust, walnut shells, fly ash, over-issue publications, textile clippings, obsolete inventories.

⁴ Post-consumer waste: Quite commonly, it is simply the garbage that individuals routinely discard, either in the

classification treats waste streams as material-related streams and product-related streams two types. For material-related streams, like metals, glass, paper and cardboard, plastics, and other recyclable waste (eg. wood waste, rubber waste, discarded textile, and bio-waste); for product-related streams, like packaging, waste of electrical and electronic equipment (WEEE), batteries and accumulators, end-of-life vehicles, etc. (EP, 2015).

Here we focus on the former: material-related streams. Within circular economy thinking, the recycling of waste materials is often categorized based on the product, which is manufactured from the secondary raw materials, hence two forms of waste material recycling treatment can be determined: conventional material recycling (closed-loop recycling), new material/product from waste (open-loop recycling). Conventional material recycling involves the industrial re-manufacturing of material into similar products, maintaining their qualities (Ordonez and Rahe, 2012; Ragaert, 2017). There are many types of waste materials that have been supported by mature industrial recycling systems, such as metals, glass, paper and cardboard, plastic, rubber, wood, and textile, etc. They are also considered recyclable materials. By secondary use, considerable profit can be obtained from these materials. However, it should be pointed out here that the recycling feasibility⁵ of recyclable materials is not only related to the specific types of the materials but also affected by the composition and matrix of the materials in the product, local policies, and infrastructure (Worrell & Reuter, 2014). For example, a small amount of PVC contaminant inserted in a PET recycle stream will degrade the recycled PET resin owing to the evolution of hydrochloric acid gas from the PVC at a higher temperature required to melt and reprocess. Hence, this kind of PET mixed with a certain proportion of PVC Waste is difficult to recycle (Hopewell, 2009). Different countries with different recycling policies and the capacity of recycling facilities will also lead to differences in the recycled materials. For instance, since 2016, Germany has had the highest recycling rate in the world, with 56.1% of all waste it produced last year being recycled benefits from their establishment of the Green Dot Program (the world's first dual recycling system for collecting household and business waste) and German Packaging Act (Parker, 2020), while China has just started in this regard, big cities are taking the lead in piloting waste sorting, and plans to increase the recycling rate of 46 urban centers to 35% in the future (Ironsides 2020). Figure 3 and 4 list the classification of the main recyclable materials mentioned by the recycling industry, sources, examples and potential recycling obstacles, as well as some important aspects that need to be considered regarding the effective closed-loop recycling process (Ragaert, 2017; European Parliament, 2015). Figure 5 shows the total amount of different types of municipal solid waste (MSW) and the share of each type of waste material being recycled. Here is the United States as an example (EPA, 2019). These information can give us a basic understanding of the current status of recyclable material recycling.

trash can or a dump, or by littering, incinerating, or pouring down the drain. Examples: newspapers discarded after reading, construction and demolition garbage, etc.

⁵ The recycling feasibility here is considered from two aspects, social-economic feasibility, and environmental-technical feasibility. Not all recycling is beneficial. We need to consider factors such as the energy consumed in recycling and the economic value of the final recycled products to determine whether it has played a better role in managing natural resources and the environment.

	CATEGORIES	SUB CATEGORIES	SPECIFIC CASES (PIW., PCW.)	OBSTACLES DESCRIPTION
Recyclable solid waste material (RSWM)	Metallic waste	Ferrous(F) eg. iron, steel (Worrell & Reuter, 2014, p. 68)	PIW. - Home scrap eg. steel reverts from the furnace surrounding, cut off from rolling, etc. - Manufacturing scrap eg. scrap from punching, overproduction waste, etc. - Other secondary material eg. shredder ferrous metal material, etc.	<ul style="list-style-type: none"> - Low scrap quality (eg.excessive copper proportion in scrap steel will make final recovery steel low quality) . - Difficulties in sorting process (eg. inappropriate liberation, inappropriate particle size for the separation process used for certain waste scenario) . - Quality loss problem (Worrell & Reuter, 2014, p. 80)
			PCW. - Obsolete waste eg. end-of-life vehicles and other consumer products, construction waste, etc.	
		Non ferrous(NF) eg. copper, zinc, aluminium, lead, rare metals, etc. (Worrell & Reuter, 2014, p. 85-148)	PIW. - Home scrap eg. copper scrap generated at the smelter, ashes and slags from foundries, etc. - Manufacturing scrap eg. scrap from galvanized steel sheet production, copper trimmings, etc. - Other secondary material eg. shredder non-ferrous metal material, sludges and combustion ashes, etc.	<ul style="list-style-type: none"> - Increasingly complex composition eg.copper recycling - complex composition of primary ores and secondary materials (Worrell & Reuter, 2014, p. 91) - Existing form of the material in the product eg. scrap of various zinc products have different recycling rates (Worrell & Reuter, 2014, p. 113) - Very complicated process for rare metals, not always economically recyclable according to some specific waste materials (Worrell & Reuter, 2014, p. 125)
			PCW. - Obsolete waste eg. end-of-life vehicles, batteries(lead), automotive catalytic converters and WEEE(rare metal) and other consumer products, construction waste, etc.	
		Mixed F and NF		
	Plastic waste	Thermoplastic eg. PET, HDPE, LDPE, PP (ISM Waste & Recycling Team, 2021; Ragaert, 2017)	PIW. - Manufacturing scrap eg. runners, fallout products, multilayer foils & sheet cutting edges, changeover etc.	<ul style="list-style-type: none"> - Two incompatible plastic components in one material - Complex additives in plastic products, such as plasticizers, pigments - Due to product design and other factors, hard to separate plastic parts from other material parts. eg.mold-in insert, complex layer structure products such as carpets
			PCW. PET eg. soft drinks bottles, fibre for making clothing (polyester), food and drinks packaging etc. HDPE eg. plastic bottles, plastic bags, plastic bottle caps, utility pipes, pens etc. LDPE eg. sauce/condiment bottles, plastic bags, bubble wrap, plastic tubing etc. PP eg. medicine bottles, packaging, bottle caps, straws, plastic bags etc.	
	Paper, and cardboard waste	Different paper grades for recycling (Worrell & Reuter, 2014, p. 167-168)	PIW. eg. pulp substitutes, paper abandoned before it reaches consumers	<ul style="list-style-type: none"> - Paper property, degree of contamination - The recycling rate varies greatly between different paper grades - if high brightness, strength or softness are required, recovered paper can only be used to a limited degree. - If the requirements for paper are too high, recycling paper will pay higher energy consumption than the primary materials
			PCW. eg. old corrugated containers(OCC), old newspaper(ONP), high grade deinked paper, mixed paper (EPA, 2016)	
	Textile waste, leather waste, rubber waste	Natural & synthetic fiber eg.cotton, wool, polyester, nylon and spandex, etc. (Worrell & Reuter, 2014, p. 211-214)	PIW. eg. by-product fiber, textile and cotton, etc.	<ul style="list-style-type: none"> - Recycling systems have difficulty accepting surprisingly high textile quantities - Changes in textile composition and property increase the difficulty of recycling. eg.high-strength synthetic fibers in textile waste are difficult to shred, and fiber mixtures hinder the purification and sorting process - Open loop recycling is encouraged, treating old to new products
			PCW. eg. garment, house article, etc.	
		Synthetic leather eg. polyurethane(PU) (Kemonia, 2020)	PIW. eg. scraps from polyurethanes manufacturing	
			PCW. eg. PU foam: discard mattresses, rebond cushioning for carpet, etc.	
		Rubber eg.natural rubber, butadiene rubber, styrene butadiene rubber, etc. (Green Rubber, 2019; Moore, 2019)	PIW. eg.waste produced during manufacturing processes and discarded products containing rubber such as latex examining gloves.	
			PCW. eg. end-of-life-tyres, miscellaneous rubber parts, etc.	
	Biomass waste	Vegetal, Animal and mixed food waste (Bouillon, 2019)	PIW. eg. waste from food preparation and products: fruit peels, shells, scraped portions of vegetables or slurries, residual milk, fish skin, feathers, bones, etc.	<ul style="list-style-type: none"> - Due to the large water content of biological waste, recycling through landfill or incineration will cause soil and air pollution. It is recommended to recycle by composting.
			PCW. eg.mixed wastes of home food and products: biodegradable kitchen/canteen wastes, and edible oils and fats, etc.	
		Animal faeces, urine and manure	PIW. eg.chicken manure, cow dung, etc.	
		Wood waste (Worrell & Reuter, 2014, p. 151-155)	PIW. eg. residues from silviculture, secondary processing sawdust (such as doors and window frame making)	<ul style="list-style-type: none"> - Some areas still mainly use landfill as a disposal method. (eg.North America) , however, wood recycling encourages higher value use before landfill.
			PCW. eg.large wood frames for construction, wood made consumer products	
	Glass waste	Glass (Worrell & Reuter, 2014, p. 191-192)	PIW. eg. waste from glass cullets, etc.	<ul style="list-style-type: none"> - Pollution of glass waste eg.mixed with other construction material - Limited recycling: Recycle the valuable mercury and rare earth phosphors in fluorescent tubes made of glass instead of glass (Worrell & Reuter, 2014, p. 193)
			PCW. eg. flat glass, container glass, glass cookware, windshields , glass component used in electronic equipment	
	Misc. inorganic waste	Cement, mineral waste, sludge and ash waste	PIW. eg.gypsum waste, stone etc.	
			PCW. eg.brick, ceramic tile, etc.	

Annotation

Category: This classification chart is made by the author based on the "Guidelines for Classification of Wastes According to EWC-Stat Category" (Eurostat, 2010). It does not include all the recyclable solid waste materials in Eurostat classification, but consider the solid waste treatment of recyclable materials with a proportion of more than 1%(consider as mainly recyclable materials) (Eurostat (env_wastrt), 2015).

Sub-categories: Each category has corresponding sub-category materials. They are representative and usually have mature closed-loop cycle systems, and are classified in more detail according to whether the source of waste is post-industrial or post-consumer.

Obstacles description: obtained from the handbook of recycling reference, some commentary articles, and the literature of specific recyclable material challenge.

Figure 3 Recyclable solid waste material (RSWM)

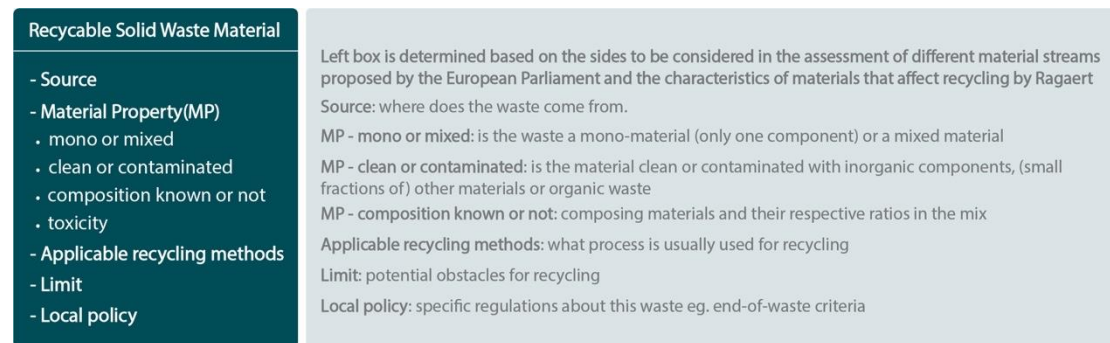


Figure 4 Important aspects considered for RSWM recycling

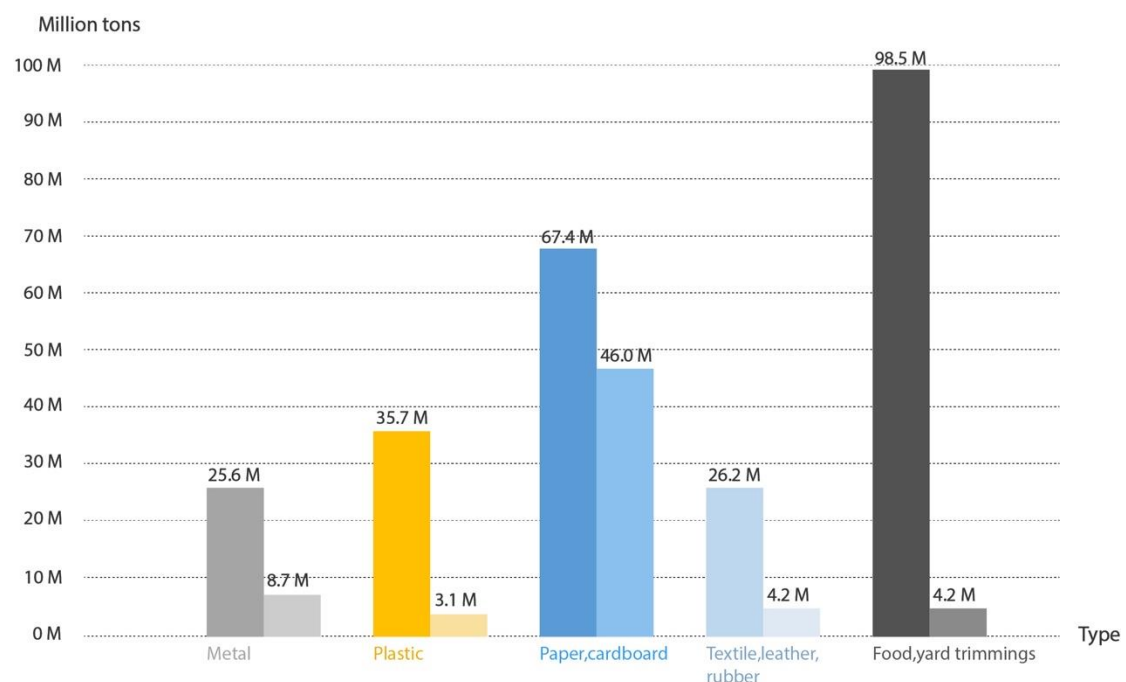


Figure 5 Total MSW Generated by Material vs. Total MSW Recycling by Material (2018, USA)

New material/product from waste means the development of products that are quite different from the original waste use (Ragaert, 2017) (Figure 6). For example, textile fiber is made from PET bottles or bio-polymer made by crustacean waste (Kunststofindustrie, 2015; Faisal, 2018). Designers and waste management practitioners consider what new materials/products can be further developed from waste in addition to following the conventional recycling track, so as to embody the concept of “uprecycle⁶”. One of the most representative phenomena is the conversion of recycled pet bottles into fiber materials, it is reported that the fiber obtained from PET flakes has a dominant proportion among end-users as 44% of the total market share in 2016 and is widely used for various textile, carpet underlays, blankets, etc (Sarioğlu, 2017). According to Bahrudin’s research, it is found that waste materials comprise up to half of the materials used by examining 72 projects focusing on sustainable materials that are being developed and applied in product design (Bahrudin et al., 2016). Some of them have unique

⁶ Uprecycle means reuse (discarded objects or material) in such a way as to create a product of higher quality or value than the original (Oxford dictionary).

aesthetic value to attract consumers, such as Swiss luggage brand-Freitag, converting waste canvas into fabrics with customized and unique patterns and make them into backpacks (Freitag Production, n.d.), and some are from waste that poses a huge threat to the environment. The products made from these wastes not only meet the use function but also have important significance for social transformation and environmental protection, such as Adidas ocean plastic shoes: the fabric on the surface of the shoe body is made of waste plastic collected from the Maldives waters, and the production of fabric made from discarded pineapple leaf materials of Philippines stimulated local income and employment growth (Adidas x Parley | Five Year Anniversary, 2020; Piñatex Report, 2021).

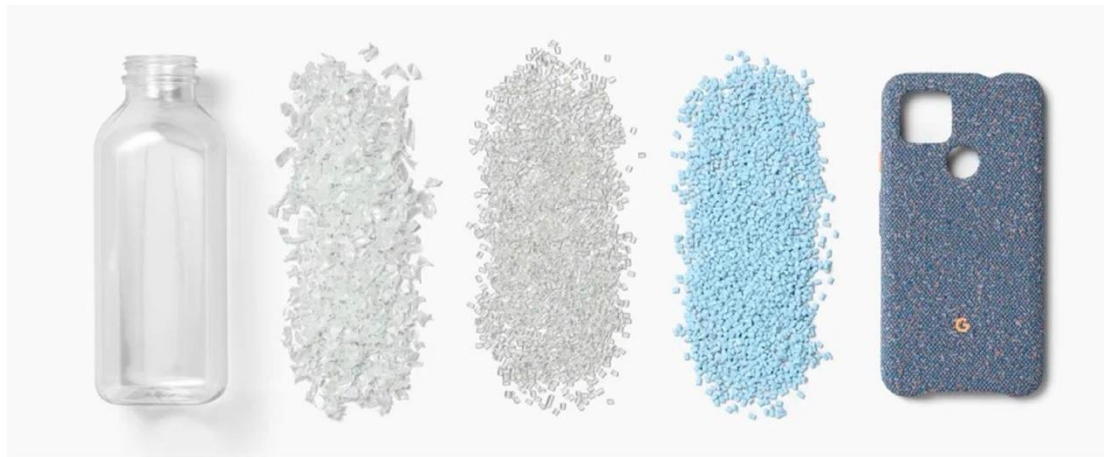


Figure 6 Google Pixel 5 case made by fabric from old PET bottle

1.2 Study Topics and Research Path Design

This thesis will focus on the new materials from waste. These new materials are quite different from the original waste use and obtained through uprecycling process. This article refers to these new materials as “recycled materials”, which are also the study focus of this thesis. Encouraged by the phenomenon that these recycled materials are actively developed by designers and gradually prosperously used in a large number of products, this paper tries to propose a recycled material database for product designers to better apply them on project at hand. Here an exploration to understand the relationship between recycled materials and product design, material selection activities and CMF design practice is conducted to support the design of the database, and the specific research path is designed as follows (Figure 7):

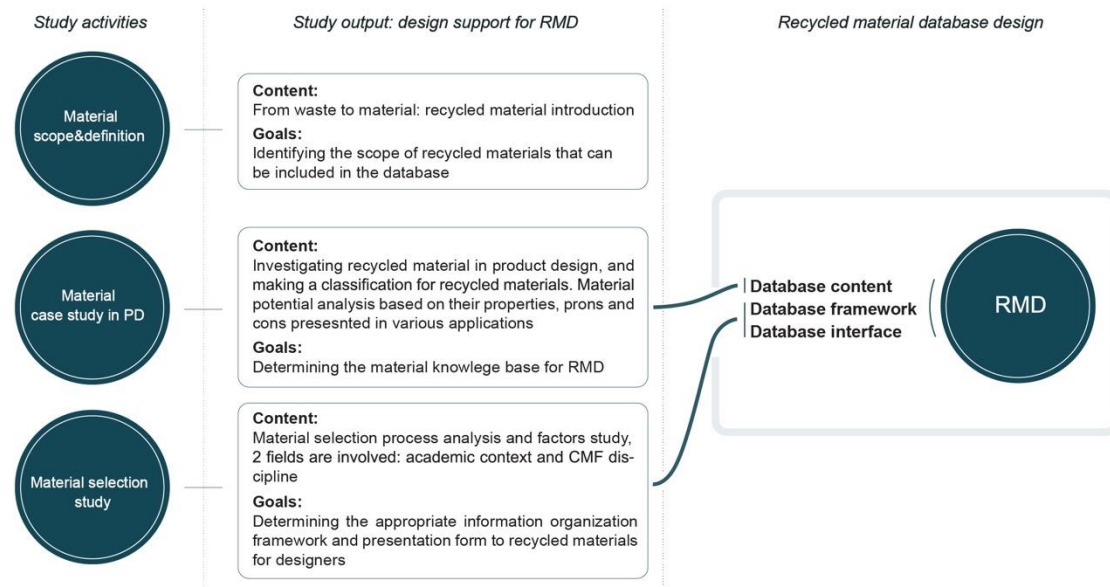


Figure 7 Research path design

- Step 1: Material scope and definition (discussed in Chapter 1)**

Examining what is a recycled material and the context in which it arises. The purpose is to identify the concept of recycled materials discussed in this paper and the range of recycled materials that should be included in the database.
- Step 2: Case study of the applications of recycled material in product design (Chapter 2)**

Carrying out recycled material case study. The purpose is to collect and investigate the current status of applications of recycled material in product design and analysis of material characteristics and use advantages, and finally determine the knowledge related to recycled materials and product design. These findings will serve as the material knowledge base of the recycled material database.
- Step 3: Material selection study in product design (Chapter 3)**

One of the important tasks of a product designer is material selection. In this step, material selection process analysis and factors study are conducted, 2 fields are involved: academic context and CMF discipline. These findings will determine the appropriate information organization framework and presentation form to recycled materials for designers.
- Step 4: Designing a recycled material database (Chapter 4)**

Recycled material database (RMD) is developed based on knowledge from step 2, 3

Chapter 2 Recycled Material in Product Design

2.1 Recycled Material Cases Study

Materials stimulate designers to create new product forms. Designers will also explore based on materials, very much hope to see new processes and applications to create new products, but must understand the impact of materials on the environment, otherwise, the design opportunity with materials will gradually disappear due to resource crisis (Dehn, 2014). Nowadays, some researchers have examined recycled materials and explored the potential of waste materials from a design perspective. For example, Sauerwein (2017) tried to understand the aesthetic quality of waste materials, believing that the consistency or inconsistency between the visual and tactile qualities of the materials would affect the aesthetic appreciation of the materials, for example, designers are more willing to use materials with coarse fiber visual quality contrast smooth tactile compared to similar quality material (Sauerwein, 2017). It is undeniable that a large number of recycled materials have been developed and applied to specific products (Orange Fiber, 2017; Corktex, 2017, etc.), but these products are usually driven by materials, have certain particularity. Therefore, for ordinary product designers, recycled material ability may be ignored, designers usually do not consider them as competitive candidate materials compared with traditional virgin materials except for certain environmental benefits. Given this, this case study attempts to make a breadth of product application analysis of existing recycled materials. A total of 54 material cases and products made from them are collected, the methodology will be better explained below. The study purpose on this chapter is to investigate the characteristics of recycled materials and their potential in product design, try to answer the following questions:

- ***Q1) Which recycled materials are used in product design and how to classify these materials?***
- ***Q2) How are different types of recycled materials manufactured? They are applicable to which fields and what is the scope of application of the material? (is the material only suitable for specific products? is the material suitable for mass production?) and what are their potential for application?***

2.2 Methodology

Study method

A total of 54 recycled material cases were collected and analyzed from online resources (The cases are presented in Appendix 1, 2 – Recycled material case study form: Material-Product), and the standards for collection are:

- 1) The material is developed from one or more waste materials, and the new material is different from the original waste use.
- 2) Recycled materials should be used in product design or have application potential, so they can be commercial materials (CM) or experimental materials (EM). Product design categories

cover the following industries: household products, architecture & interior, packaging & disposable products, textiles, furniture and others.

The collection domain: online material library (eg. Material District, Rematerialize); published information of commercial organizations, material lab and design workshops; design news website; some academic literature discussing the application of recycled materials.

The information collected is

- 1) Basic information on recycled materials: year of first report, reference link, market availability, raw materials (recycled material name/feedstock for recycled material), manufacturing (material manufacturing process/stock form: what form of raw materials are usually processed into/production scale)
- 2) Information about products made of collected recycled materials: products, company, and material potential (what are the advantages and disadvantages of materials: examine three aspects: technical characteristics/aesthetic characteristics/sustainable characteristics). Three aspects of aesthetic characteristics will be recorded according to documentation found : color and appearance quality, touch and visual quality. The sustainability characteristics are recorded from three aspects according to the type of waste and the final material report: whether the raw material is renewable, whether the final material is recyclable and/or biodegradable.

2.3 Results and Discussion of the Case Study Analysis

2.3.1 Recycled material classification and answer for Q1

According to the collected data, the number of commercial materials accounted for 64% (44 cases are found), and experimental materials accounted for 36% (25 cases are found). Most of the materials come from Europe (47 cases), of which the Netherlands is the most (21 cases), this may be related to the bias of the main collection domain-material district which comes from the Netherlands, followed by the United States (12 cases). Of all materials, leading by enterprise accounts for 57% (39 cases), and individuals or studios account for 43% (30 cases). The proportion of waste sources in descending order are biomass waste (24 cases), synthetic plastics (17 cases), construction and other inorganic wastes (such as stone, glass, etc., 16 cases), and mixed waste (such as material made from quartz and PET, etc. 12 cases), see Figure 8

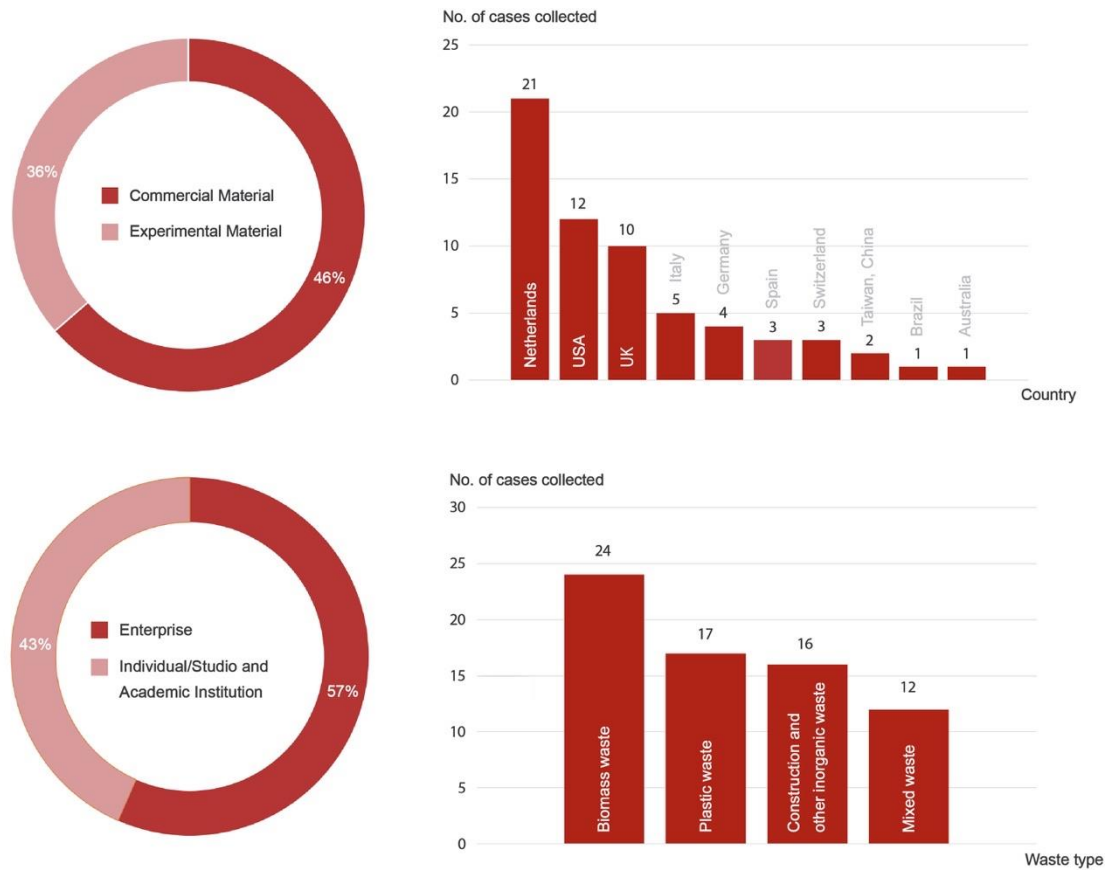
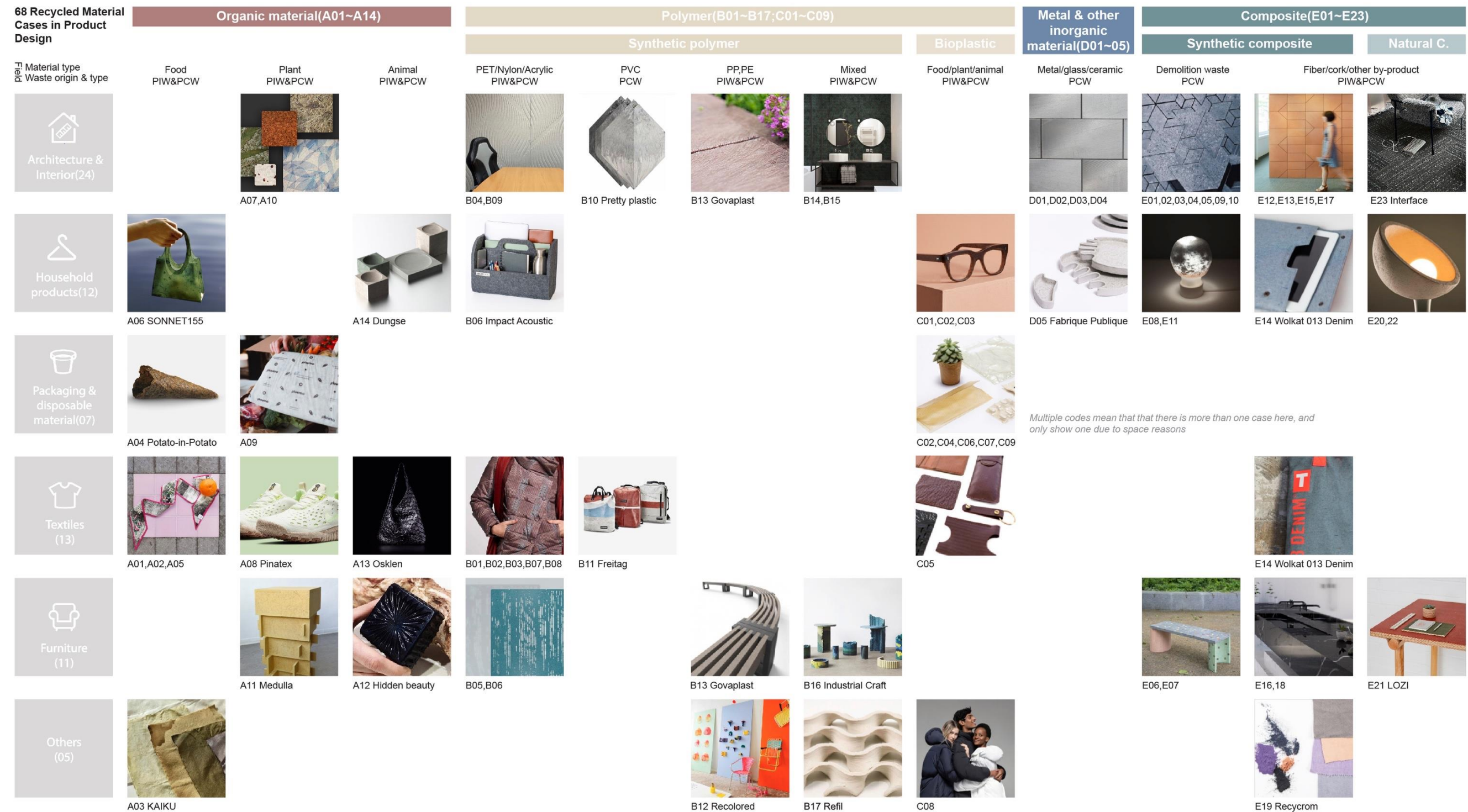


Figure 8 Recycled material case data statistics

Material classification allows us to have a global understanding of their similarities and differences, and their basic properties, so that we can apply them more in-depth later. At present, there is no systematic classification of new materials obtained from waste. However, when relevant studies classify sustainable materials, it is mentioned that new materials can be classified according to the source of waste materials: new materials from by-product waste⁷, new materials from the second life⁸ (Bahrudin et al., 2016). In addition, some material libraries centered on sustainable materials also contain different types of recycled materials. For example, the Rematerialise library has established its own material classification rules to classify some waste streams that are difficult to collect as easily overlooked materials (Dehn, 2014).

⁷ Material made from waste that is a left-over of a production process (Bahrudin et al., 2016).

⁸ Material made from waste that is obtained from a product which has researched its end of life (Bahrudin et al., 2016).



NOTE: Detailed case analysis presented in thesis chapter 2 by code, PIW (post-industrial waste), PCW (post-consumer waste)

Figure 9 Recycled material classification design based on applications in product design and material composition

Here, based on the final material composition of the collected cases and the characteristics of the waste source recycled materials are divided into 4 categories: Waste-based organic materials, Waste-based polymers, Waste-based metal and other inorganic material, Waste-based composite material. It is further subdivided according to the material sustainability: Waste-based polymers are divided into waste-based synthetic polymers and waste-based biopolymers. According to whether the matrix in the composite material is composed of natural waste or synthetic waste, waste-based composite material is divided into Natural composite from waste (matrix is composed of natural waste) and Synthetic composite from waste (matrix is composed of synthetic waste), this definition is based on following reasons: the proportion of matrix material in composite is larger than the reinforced material, so the matrix material has a greater impact on the environment. In addition, the materials are further organized according to the field of application and availability, so that designers can get inspiration from recycled materials. The complete classification diagram is shown in Figure 9

The horizontal axis of the table is the category of recycled materials, and the vertical axis is the different application industries. The content of the table is the name of the material and the waste materials used. The green text represents the commercially available materials that can be produced on a large scale, and the gray text represents that the material is still in the experimental development stage or is only suitable for small batch production. Therefore, this can provide designers with an insight into the potential of recycled materials in different industries. Designers can search for recycled materials with application potential according to the material type and project field.































































2.3.2 Waste-based organic material

Material class definition:

Materials made from biological waste, such as pineapple leaf fiber (PALF)-based materials, materials made from animal remains, orange fibers obtained from fruit peels, etc. Common sources of biological waste, for instance, plant waste (such as by-products from plant growth, waste leaves, abandoned straw, etc.), animal waste (such as animal feces, carcass, etc.), and food waste (such as waste peels from food processing industry, fish skins, etc.)

Material manufacturing and Scope of application analysis:

A total of 14 material cases have been collected (as shown in Figure 10), of which 6 are inedible parts of food waste (case A01-A06), 5 are from by-product waste produced by plant growth (case A07-A11), and the other 3 are from animal waste (A12-A14). Among them, 6 kinds of materials can accept mass production, the form of raw materials is mainly cloth (eg. A01, A02, A05, A08). 8 kinds of materials can be produced in small batches, they are experimental materials, rich in forms, including sheets, cloths, blocks, powders, and liquids (eg. A03, A04, A06, A10-A14).

Waste Group		Raw material (name/feedstock)	Developer/Year	Manufacturing (recycling method/scale/stock form)	Application
Organic Material	Food Waste	A01  Qmilk / Spoiled milk	Qmilk, Germany / 2018	Chemical recycling / Cloth  	 Fabric / apparel, bed linings
		A02  Orange fiber / Citrus juice by-products, other fibers	Orange fiber, Italy / 2017	Chemical recycling / Cloth  	 Fabric / apparel
		A03  Bio-derived pigment powder / Fruit and vegetable peels	Nicole Stjernsward, UK / 2019	Physical recycling / Powder  	 Dye / Fabric dyeing for garments or canvans
		A04  Potato Food Packaging / Starch, lettuce, fiber extracted from dehydrated potato peels	Simone Caronni, etc. Portugal / 2017	Chemical recycling / Film  	 Potato made paper / ice-cream package, etc.
		A05  Fruit leather / Left-over fruit, animal hide waste	Fruit leather Rotterdam, Netherlands / -	Chemical recycling / Cloth  	 Leather / footwear, fashion accessory, interior and furnishing industry.
		A06  SONNET155 / Left-over fruit	Lobke Beckfeld&Hemeyer-Cürten, Germany / -	Physical recycling / Cloth  	 Leather / fashion accessory, shopping bag
	Plant Waste	A07  Organoid / Different kind of nature waste from Alpine, ecological binding agent	Organoid, Austria / 2013	Physical recycling / Sheet, bulk   	 ORGANOID natural surfaces / wall decoration, flooring panels, acoustic elements, etc.
		A08  Pineapple leaves fiber / Pineapple leaves waste	Pinatex, UK / 2015	Physical recycling / Cloth  	 PLFA fabric / many kinds of textile, such as apparel, bag; furniture surface treatment
		A09  Sustainable feather-based insulation material / Waste feathers	Aeropower, UK / 2017	Chemical recycling / Film  	 Package paper / package paper used in food or pharmaceutical deliveries
		A10  Foamy composite bio material / Sunflower crop waste	STUDIO THOMAS VAILLY, Netherlands / 2017	Physical recycling / Sheet, bulk   	 Sunflower-based bio composite panel / Wall construction
		A11  "Soft Rush" foam material / Weed waste (pith and fibers of soft rush)	Don Kwaning, Netherlands / 2018	Physical recycling / Sheet, bulk   	 Plant foam sheet / packaging material and furniture
	Animal Waste	A12  Hidden beauty / Waste from the slaughter industry(eg.animal offal, bone, etc.), resin	Clemence Grouin-Rigaux, UK / -	Physical recycling / Sheet, 3D object, bulk    	 Paint / Surface treatment with a variety of products, such as stool
		A13  Amazonian Fish Skin Fabrics / Fish skin waste	Oskar Metsavaht, Brazil / 2018	Chemical recycling / Cloth  	 Tiles / -
		A14  Dungse-based composite / Dungse waste	STUDIO CARBON AND STUDIO LINDEY CAFSIA, Netherland / 2019	Chemical recycling / Sheet, Bulk   	 Tiles / alternative for traditional materials such as (virgin) wood, plastic and other stoney materials in construction, home products and accessories

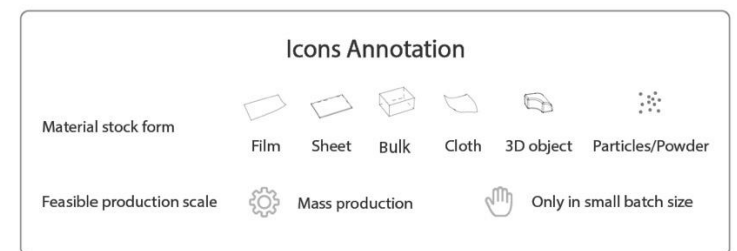


Figure 10 Waste-based organic material case study

A considerable part of materials are used in the production of cloth and leather. Cellulose, casein can be obtained from fruit and plant waste and made into fiber raw materials by chemical process. Therefore, some fabrics made from it have the advantage of biodegradability. A representative material is orange fiber (case A02), which uses citrus peel as a raw material to extract cellulose to form a high-quality silk fabric for use in the fashion apparel industry (Orange Fiber, 2017). The manufacturing process involves using two different quashing reagents (sodium sulphite and sodium metabi-sulphite) to extract cellulose from the peel (Marín et al., 2007). The main process parameters involve sulphite agent amount and the reaction period, on the yield of cellulose (Widmer et al., 2010). Then, the rudimentary cellulose are bleached with oxygen and hypochlorite. The extraction process involves controlling the physical and chemical properties of cellulose materials, such as high purity, low crystallinity, brightness, water retention and reasonable molecular weight (Inoue et al., 2010), so as to obtain high-quality α cellulose, which is then spun into filaments to obtain citrus cellulose acetylated fiber as new fiber material. Further mixing different proportions of cotton or elastic polyurethane to get a functional fabric (Orange Fiber, 2017). The advantages of this process have certain economic potential, because the current preparation of artificial high-quality α cellulose (such as visa, rayon, lyocell) is mainly based on the cellulose in wood pulp, which is expensive, hence the use of an innovative citrus peel extraction process is a new economic solution.

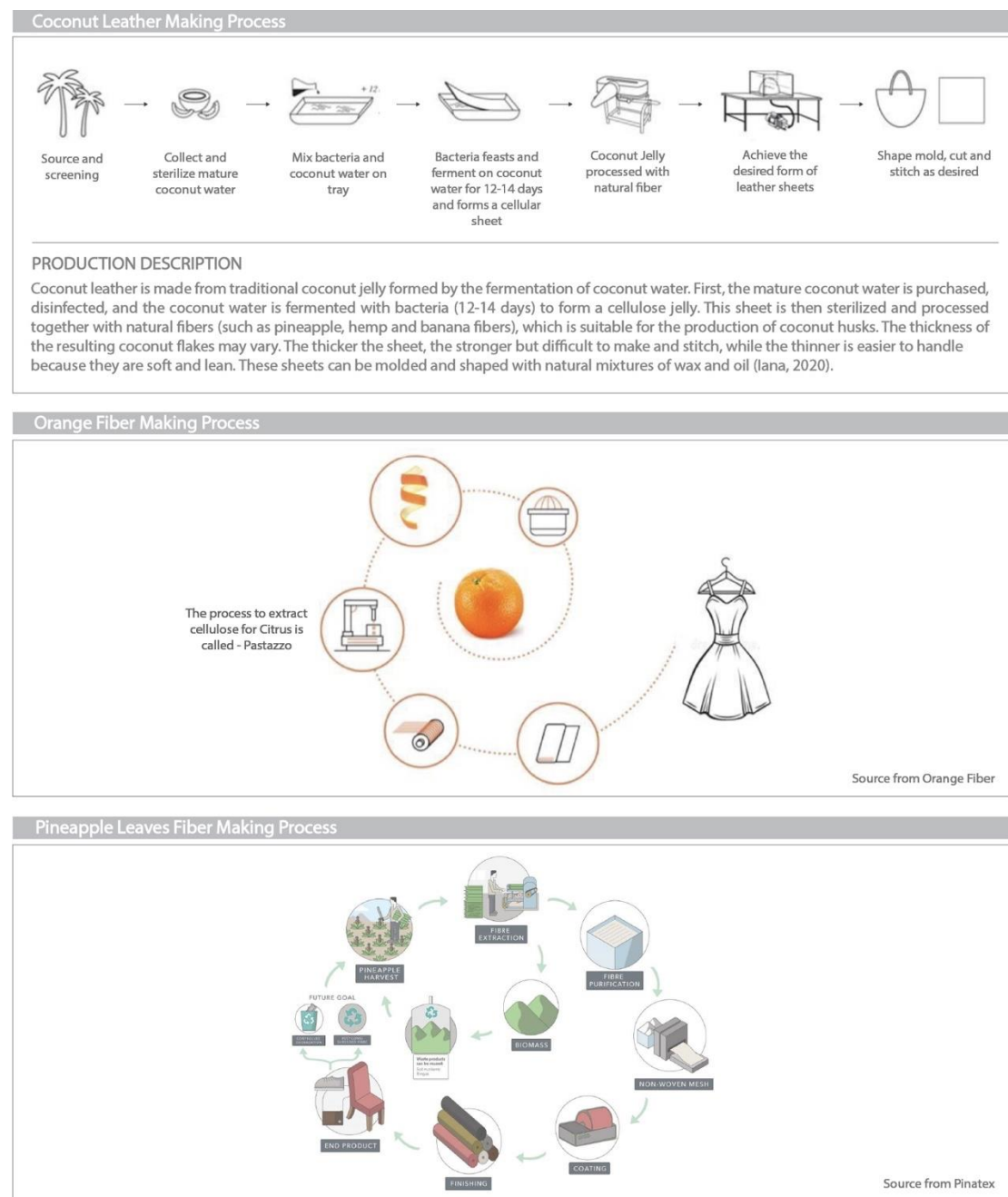


Figure 11 Three plant-based fiber making process (Coconut water / Orange peels / Pineapple leaves)

Furthermore, obtaining leather from biowaste is also a popular trend (A05, A06, A08). Some studies have summarized the manufacturing process and application potential of different leathers made from plant waste (Dushyant, 2021), as shown in Figure 11. As an unsustainable problem in the traditional leather industry (most leather manufacturing uses chromium as a tanning agent), some studies have explored the application potential of biological tanning agents and the advantages of fish skin (case A13) as a leather raw material (Duraismy, 2016). For example, leathers with different colors and textures can be obtained using different vegetable tanning agent: hydrolyzable tannin blends (derived from bark material) make leathers become pink, red or dark brown shades that are more 'solid'. However, the leather made with condensed tannin is light-colored, ranging from cream or light yellow to light brown.

They make the leather pleasant to the touch and achieve rich tonal variations. The principle of using biological tanning agent to make fish skin based leather is that the phenolic molecules present in the tanning agent form a complex reaction with the collagen in the fish skin, thereby converting the perishable skin or raw hide into a non-perishable material. The tannin content and structure of different vegetable tannin give the final leather different elasticity. In addition, different types of fish skin have different textures. For example, stingray skin has small teeth instead of scales, which give the finished leather a charming appearance. Each species has a unique exotic scale pattern, and we can get richly colored leather from discarded fish skins (FASHIONUNITED, 2019).

The other materials in the collection cases present a wealth of application forms (A03, A04, A07, A09-A12, and A14). For example, Organoid (case 07), by utilizing natural waste or from the waste provided by customers, unique veneers with aesthetic quality was developed and being used in many types of carriers, such as high-density laminates with cocoa bean texture on the surface or felt cloth with the texture of Alpine wildflowers, which apply to fields of furniture veneers, interior decoration, etc. The manufacturing process is similar to making traditional plant specimens. According to the type of carrier material to choose whether to heat press or adhesive. Interestingly, the company has studied the possibility of transforming different bio waste materials into final graphic patterns and tried to combine with popular color trends to achieve competitive decorative panels, Figure 12 (Organoid, 2020).

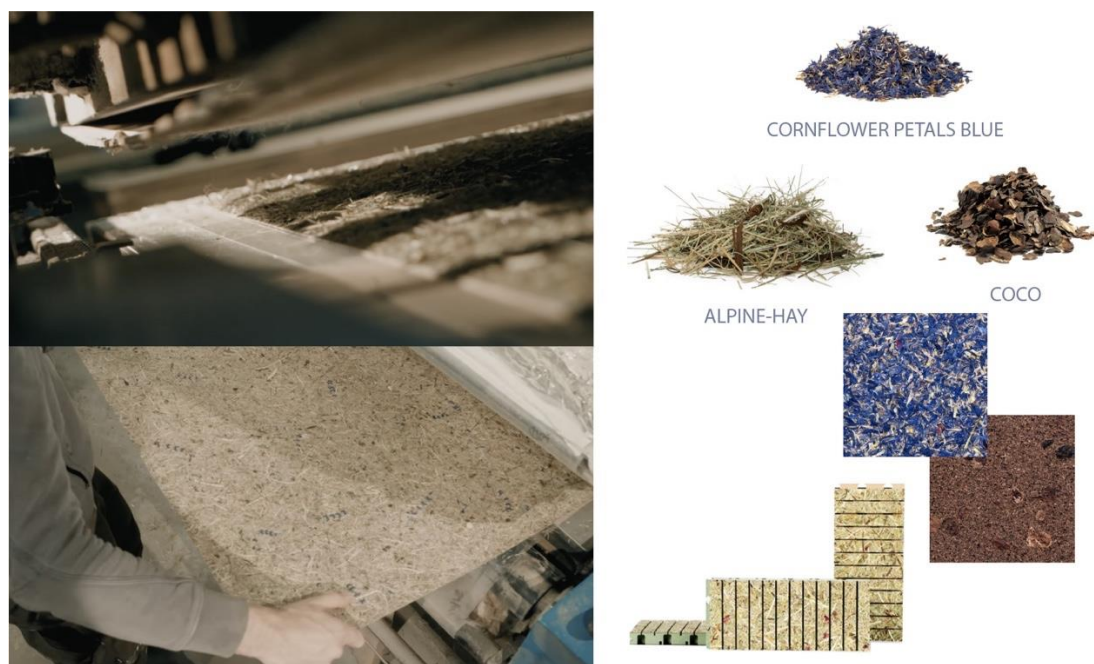


Figure 12 Natural plant based material for panel developed by Organoid, Heat press process and final sample(Left), From natural waste to natural pattern (Right)

Case A04, A09, A10, and A11 show the potential of recycled organic materials in packaging fields. For example, in A09, the author developed soft-rush material inspired by the craft of Japanese tatami (a flooring material woven from weeds). The pitch and fiber components are separated from the soft-rush. The former is made into a light foam-like material, which is

similar to fiberboard, and can achieve a variety of densities without adhesives, and can be used to make packing and storage boxes. The latter can be used as a building material and can be used as a lightweight furniture material (INHABITAT, 2018). A10 shows another similar example. The author used the plant waste from sunflower seeds to develop water-based glue, light foamy composite material (from the pitch), and hardboard (from bark fibers). Designers believe that these bio-based materials hold rich characteristics and expect to have further applications in fields of heat insulation, sound insulation panels, office furniture, and disposable packaging (STUDIO THOMAS VAILLY, 2017).

Other designers pay attention to waste materials which are easily overlooked. For example, Clemence Grouin-Rigaux (case A12) explores animal waste in slaughterhouses. By heating, mixing resin to produce a black viscous liquid, it can be used for a series of molded products and a set of animal waste-based material samples have been developed (as shown in Figure 13). Grouin believes that a considerable amount of animal bones and innards are wasted due to people's squeamishness on them, and eventually, they end landfilled, leading to decay, negatively affecting environmental and animal health. Therefore, these wastes should be valued to change people's perceptions of them (Clemence Grouin-Rigaux, 2019). Nicole Stjernsward tried to boil plants and fruits rich in natural pigments such as avocados, onions, and oranges in water so as to acquire filtrate (dye from plant waste). Then, by vaporating it, the solid color powder was extracted, which can be used for painting and textile dyeing (Nicole Stjernsward, 2019). Lobke Beckfield and Hehemeyer-Cürten from Germany have found that the gelling agent can be extracted from the cell wall of waste fruit and used as a natural binder to mix it with fiber waste to form a peel-like material. By controlling the fiber's length and density, the transparency and elasticity level of the material can be adjusted, and by using different mold structures to prepare, the material surface can turn from dull to glossy (FUTUROPROSSIMO, 2021).



Figure 13 Material exploration from animal waste in slaughterhouses by Clemence Grouin-Rigaux

2.3.3 Waste-based polymer

Part 1: Waste-based polymer

Material definition:

New material developed from petroleum-based plastic waste. The main source comes from abundant plastic waste from consumer goods, such as PET bottles, disposable products made by PE and other textile waste made by plastic, etc.










































































Waste G.	Raw material (name/feedstock)	Developer/Year	Manufacturing (recycling method/scale/stock form)	Application
PET / Nylon / Acrylic Waste	B01  Recycled PET blend / Polyester, PET, other eco-friendly cotton wool waste	Waste2wear, Netherlands / 2010	Physical recycling / Cloth  	 Textile / promotional business, interior decoration, etc.
	B02  REPREE FIBRES & FABRIC / PET bottle waste	Repreve, USA / 2018	Physical recycling / Cloth  	 Textile / various features of fabrics for athletic and fashion apparel and more
	B03  Ecolution Recycled Nylon Fabric / Polyamide from post-industrial waste products	Jou Jou Fish, Taiwan / 2019	Physical recycling / Cloth  	 Fuctional Fabric / -
	B04  Recycled PET felt wall-paper / PET waste	RTS-PREIDEL, Netherlands / 2020	Physical recycling / Sheet  	 RTS acoustic panels / Customized wall surface treatment, furniture surface treatment
	B05  PET FELT ACOUSTIC PANELS / PET waste	Refelt, Netherland / 2019	Physical recycling / Cloth, Sheet   	 Acoustic panel, tile / baffles, interior decoration, furniture surface treatment, etc.
	B06  Impact Acoustic / PET waste	Switzerland / 2020	Physical recycling / Cloth, Sheet   	 Acoustic panel, tile / ceilings, interior decoration, accessory, furniture surface treatment, etc.
	B07  The ECONYL® yarn / Nylon waste from finishing net, cloth, etc.	Aquafil, Italy / 2011	Physical recycling / Cloth  	 Textile / various features of fabrics for fashion apparel and more, carpet, etc.
	B08  90% Patagonia / Post-consumer and post industrial nylon waste	Patagonia, America / 1973	Physical recycling / Cloth  	 Textile / various features of fabrics for athletic and fashion apparel and more
	B09  Raytent fabric / Acrylic fabric waste from discard carpets	F.lli Giovanardi, Italy / 2019	Physical recycling / Cloth  	 Textile / Outdoor furniture, garden and pool furniture, in particular cushions for sun loungers, sofas, chaise longues and chairs, pergolas and fixed structures.
PVC Waste	B10  Pretty plastic / PVC waste from building sector	Pretty Plastic, Netherland / 2017	Physical recycling / 3D object  	 Tiles / Building facade covering material
	B11  Freitag / Waste truck canvas (mainly post-consumer PVC)	Freitag, Switzerland / 1993	Physical recycling / Cloth  	 Fabric / bags, wallet, notebook cover, key chain
PP, PE Waste	B12  Recolored / Plastic waste streams in different color, such as HDPE, etc	Jessicadenhartog, Netherland / 2018	Physical recycling / Slab, sheet, film    	 Woven plastic fabric / -
	B13  Industrial Craft / Post-consumer PE, PP waste	Govaplast, Belgium / 1995	Physical recycling / Slab, Sheet, 3D object    	 Govaplast panel / planks, floors, fences, furniture, and playground equipment
Mixed Polymer Waste	B14  Plasticiet / Discarded plastics (LDPE-HDPE, PS, ABS)	PLSTCT, Netherlands / 2019	Physical recycling / Sheet  	 Plastic sheet / furniture making, interior design, displays and purely decoratively
	B15  Plastic stone tiles / Post-consumer plastic waste	ENIS AKIEV, Germany / 2018	Physical recycling / Sheet  	 Tiles / -
	B16  Industrial Craft / Plastic waste streams associated with CNC fabrication (eg. polyurethane foam dust from CNC 3D production)	Charlotte Kidger, UK / 2019	Physical recycling / 3D object  	 Composite slab / Customized making(eg.sculpture,vassels etc)
	B17  Refil, fully recycled 3d printer filament / Inside of old refrigerators waste(HIPS), dashboard waste(ABS), PET package	Refil, Netherlands / 2017	Chemical recycling / filament 	 3d printer filament / prototyping making

Figure 14 Waste-based synthetic polymer material case study

Material manufacturing and Scope of application analysis:

A total of 17 cases have been collected (as shown in Figure 14). Based on different waste sources, they can be classified into the following categories: Artificial fibers, such as PET/nylon/acrylic (case B01-B09); Blended PP and PE (case B12, B13); PVC (case B10, B11); and other plastic types, including polyurethane foam or very complex blended plastics, etc. (case B14-16, B17), which are mainly post-consumer waste. The techniques applied for recycling are mainly physical recycling.

Among them, 11 kinds of materials can be mass-produced, and the raw materials are mainly fabrics and plates (B01-B09 and B11); 6 kinds of materials are feasible in smaller batches. They usually have specific effects, and some are even made into specific products such as PVC tiles (case B10). The raw materials are mainly in the form of plates and films.

Large-scale production of recycled synthetic polymers is usually based on mechanical recycling techniques, which follow the following steps: Separation and sorting-Baling-Washing-Grinding-Compounding & pelletizing (Ragaert, 2017). The obtained plastic particles can be directly used as raw materials for molded products or further processed into fiber raw materials through a melt spinning process for the fabrics. A representative example of using recycled plastic particles is Govaplast (case B13) (Figure 15). First, the company uses recycled PE-PP particles with dyes and other additives, melting them at high temperatures. Then, injecting the substance into preset molds and taking out shaped parts after cooling down. Final products have similar processability to wood, which can be used for making planks, floors, fences, furniture, and playground equipment. This material has significant advantages compared to wood and concrete, which is reflected in its weather resistance, corrosion resistance, and ease of maintenance and cleanliness. It also harmonizes well in natural or urban scenery, possessing low-saturation but high-color-richness (Govaplast, 2020). The use of recycled blended plastics in new products is a practice of uprecycling, which is rather common, owing to some plastics with similar characteristics in the waste stream are difficult to be further separated, so they are directly processed in the way of blended polymers. Generally, the characteristics of blends depend on the miscibility between the components, reflecting synergistic, antagonistic, or additive behavior. Most blends do not follow additive law due to complicated reasons, and it may be attributed to the blends being affected by unknown components in the waste, processing temperature, and other factors (Ragaert, 2017). However, by adding a suitable solubilizer, the performance of blends can be improved. For example, adding a certain amount of the solubilizer EPDM (ethylene propylene diene monomer) to PP/PE blends with a specific ratio can significantly increase the elongation at break value (Hubo et al., 2016).



Figure 15 Atlantic deck chair designed and manufactured by Govaplast (Left), Govaplast Product Series (Right)

Converting plastic waste into recycled fibers is an important means of sustainable development of textiles. Pre-consumer or post-consumer PET, nylon, and acrylic waste all have the potential to become functional fibers. Due to the limitations of recycling technology and the characteristics of waste streams, the use of PET waste in fiber manufacturing is the mainstream. A representative case is Waste2Wear (case B01), has applied PET to clothing, interior textiles, promotional materials, and other products (Waste2Wear, 2021). They have launched four fabrics with different textures, using innovative technology to make finer recycled yarns and make high-performance fabrics by redesigned weaving pattern. For example, Waste2Wear® recycled polyester sportswear is made of very high twisted filament yarns, with a high number of fibers, so it increases breathability and improves moisture absorption and perspiration, making them very comfortable to wear (Waste2Wear-sportswear, 2019).

In addition, it is also common to use recycled PET to make functional felts (case B05-B07) for indoor noise absorption and isolation purposes. A cutting-edge case is RTS-Akoestisch felt. The production process is to carefully blend recycled PET fibers to ensure that each square meter of felt shares exactly the same characteristics. The fibers are then carded into thin layers laid above each other and carded together to form a wad. The wads are processed using barbed needles, which first create and then increase the density of the felt with each pass. In the end, the high-quality felt combined with polyester wool filler can effectively reduce reverberation time and optimize the listening experience of the scene. The material surface can project full-size images, and can be decorated with customized 3D patterns (RTS-Akoestisch felt, 2020). Due to PET recycled felt has good moldability potential, it also has a wide range of applications such as furniture, backpacks, daily necessities, pet houses, etc. (Impact Acoustic, 2019; Refelt, 2020) (Figure 16).



Figure 16 Acoustic lighting by recycled PET felt (Left, Impact Acoustic) and felt shaping process (Right, Refelt)

In the mechanical recycling process, the performance of recycled PET is likely to be significantly degraded due to thermal influence and shear stress. Hence, other performance improvers, such as chain extenders, are usually added during processing to avoid degradation caused by chain scission (Ragaert, 2017). However, some chemical recycling makes it possible to obtain recycled PET with superior quality to the original material by improving the processing environment. For example, the Solid State Polymerization (SSP) technology developed by CUMAPOL can control the molecular mass level of recycled polyester to obtain particles with even better performance than the original PET. In detail, the high molecular-mass-levelled polyester with uniform and consistent characteristics and viscosity is acquired by purging the conversion furnace with nitrogen at a high temperature and zero oxygen environment before the material is extruded. During this process, the PET polyester with higher added value can be acquired by increasing the intrinsic viscosity, which can be used to manufacture molded parts used in the automobiles, packaging, fiber, and consumer goods industries (CUMAPOL, 2020).

The manufacture of recycled nylon fiber is much more demanding than the manufacture of rPET. Because nylon cannot withstand high temperatures which means thoroughly cleaning needed, and the lack of recycling equipment is another drawback (PEGEX Hazardous Waste Experts, 2017). However, recycled nylon can maintain its original quality during recycling compared with rPET, which makes it attractive. For example, it is an ideal material for recycled performance leggings for high-intensity exercises. Its perspiration-wicking, breathable, and quick-drying characteristics make it very comfortable to wear (THREADS 4 THOUGHTS, 2019). A famous promoter is Patagonia (Case B08). This company developed more than 50 products from nylon waste which comes from post-industrial waste fiber and discards from weaving mills and post-consumer fishing nets, worn-out clothes or discarded carpeting, etc. (Patagonia, 2021).

Usually, acrylic is not recyclable. However, Raytent has developed a unique technique to chop the post-consumer acrylic fabric into fibers of suitable fineness and then blend it with original acrylic fiber or other natural fibers to obtain recycled acrylic fabric (Figure 17). Material have proper color and other enhanced functions such as colorfastness to UV rays, stain-resistant and anti-mold behavior, which applies to the living application, shade and rug (Raytent, 2020).

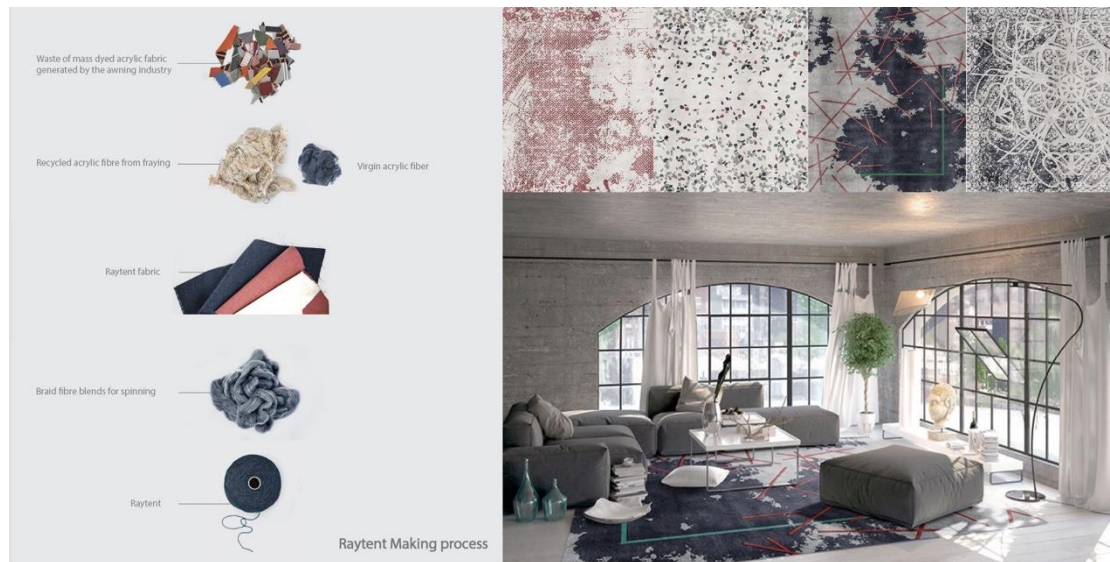


Figure 17 Raytent yarn making process (Left), material applications in rug (Right)

The customizability and exploratory is the main characteristics of small batch production of recycled polymer materials (B10, B12, B14-17). They reflect the designers and related practitioners' voice of plastic-environmental awareness and the active exploration of turning waste materials into stunning objects. Manufacturing methods for these materials are quite flexible. For example, Refil (case B17), founded by graduates of the Delft University of Technology (Waag, 2016), focuses on 3D filaments made of recycled plastics. It has developed ABS and PET filaments, which can be used for 3D printing, available in selective laser sintering, used for innovative apparel design (Francis Bitonti, 2013). Case 16 uses the polyurethane foam dust produced by CNC 3-D model production mixing with colored resins, which are then cold-formed in molds, to make vases, tables, exhibition display, and other fields. The unique natural defects formed during the casting process make the surface of the product have unique aesthetic qualities, as shown in Figure 18 (Charlotte Kidger, 2021). Given the precious quality of the various colors and the good plasticity characteristics of plastics before recycling, some organizations have conducted research on the color quality and processing characteristics of the recycled plastic after melting. A representative example is Recolored plastic workshop by Hartog, the open-source platform Precious plastic (Recolored, 2020 and Precious plastic, 2021).



Figure 18 Plastic stone tiles by ENIS AKIEV (Left), polyurethane foam dust furniture by Charlotte Kidger (Right)

In conclusion, recycled polymers occupy an important position in recycled materials. After all, white pollution has caused a significant impact on the environment, and the current recycled plastic waste accounts for only 9% of the world's total emissions (National Geographic, 2019). The industry world is striving to produce high-quality recycled polymers and is trying to expand the range of acceptable waste plastics. For recycling industry, chemical recycling is getting more and more attention. For example, gr3n up-cycling technology uses depolymerization and re-polymerization to form polymer monomers with similar original mass. Unlike traditional PET mechanical recycling, it can accept a variety of PET waste types such as polyester clothes and others. In addition, the produced recycled plastic with the same quality as the origin is also highly competitive with oil-based polymers in terms of price and can be recycled multiple times to achieve a closed-loop (gr3n, 2018).

With the rise of the DIY boom and the democratization of technology, the power of personal organizations to explore plastic waste should not be underestimated. They have made a positive contribution to changing the public perception of “disposable plastics”. Many high value-added recycled plastic products emerge, and attempt to cooperate with manufacturers.

Part 2: Waste-based bio-polymer

Material definition:

Polymer-based material developed from biomass waste, such as casein plastic (eg. bio-polymer made from spoiled milk), starch-based plastic (eg. bio-polymer made from potato peel), etc. There are many kinds of biomass waste which can work as bio-polymer feedstock, from useless residues in nature (eg.algae, miscanthus,etc.) or human production activities (eg. starch-rich food waste, coffee residue,etc).






























Waste G.	Raw material (name/feedstock)	Developer/Year	Manufacturing (recycling method/scale/stock form)	Application
Bio-polymer based on biomass waste	 C01 Parblex™ Plastics [PBX] / Different kind of biomass waste	Chip[s] Board®, UK / 2016	Biological process / Sheet, Granulate   	 Parblex™ Plastics [PBX] Series / Glasses plate, construction supporting structure
	 C02 Vibers / Potato waste, Miscanthus	Vibers, Netherlands / 2018	Physical process / Sheet, 3D object   	 various consumer products and packaging materials, eg. molded product, disposable plate, etc.
	 C03 Miscanthus biopolymer / Miscanthus, colza oil	Interessengemeinschaft Miscanthus, Switzerland / 2018	Physical process / Sheet, 3D object   	 Biodegradable flower pot
	 C04 The Shellworks / Seafood waste	Ed Jones, Insiya Jafferjee, Amir Afshar, and Andrew Edwards, UK / 2019	Chemical process / Sheet, Film, 3D object    	 Anti-bacterial blister packaging and food-safe carrier bags to self-fertilising plant pots.
	 C05 Tömtext / Waste seafood shells, coffee grounds, natural pigments such as charcoal, coffee and ochre	Uyen Tran, - / 2020	Chemical process / Cloth, Film    	 Different surface leather textures can be customized for decoration accessories, wallet etc.
	 C06 Coffee based polymer / Coffee grounds	Coffee Based, Netherlands / 2016	Physical process / Sheet, Granulate   	 Cups and other molded products
	 C07 Algae based polymer / Algae waste	Studio Klarenbeek & Dros, - / 2017	Biological process / Film  	 Utensils
	 C08 FLWRDWN-vegan and plastic free down alternative / Biopolymer enhanced with wildflowers, aerogel	Pangaia, - / 2019	- / -  	 Vegan and plastic free down alternative for down jacket liner
	 C09 Cellulose and chitin based polymer / Waste contains cellulose and chitin	Georgia Institute of Technology, - / 2018	Chemical process / Film  	 Packaging film

Figure 19 Waste-based bio-polymer material case study

Material manufacturing and Scope of application analysis:

Biopolymers have become a potential material to replace petroleum-based plastics thanks to their degradability, low impact, and many other enhanced performance. There are relatively mature applications in the packaging and textile industries. However, appearance in the field of product design is relatively recent. Biopolymer case study in this investigation are all developed from biomass waste, involving applications in shoes, furniture, toys, utensils, and other fields. (Figure 19). Many of these materials adapt to mass-produced for injection molding and compression molding products. The raw materials are mainly particles and sheets (case C01, C02, C03, C06). Other designers and research groups experimented with bioplastics made of various materials, from corn starch to beetle shells (case C04, C05, C07-09).

Bio-based polymers can be divided into three categories according to their source and production: 1) Polymers directly extracted/removed from biomass such as polysaccharides (e.g., starch and cellulose) and proteins (e.g. casein and gluten); 2) Polymers produced by classical chemical synthesis using renewable bio-based monomers, such as polylactic acid, formed by polymerization of lactic acid monomers fermented from carbohydrate-rich raw materials, 3) Polymers produced by microorganisms or genetically modified bacteria (Weber, 2000, p. 14). Biopolymers obtained from starch-containing wastes have mature applications in many fields. They can be biodegraded to a large extent and are biocompatible. Starch can be obtained from wastes containing potato, corn, and other starting crop wastes, and the biopolymers can achieve their excellent performance by blending with other reinforcing materials, such as natural fiber. The processing flow is: the starting materials, most of which are in the form of polysaccharides, are extracted from plants through the wet-milling. Then, starch is used in its original state or further processed by bacterial fermentation to produce bio-based monomers, and finally polymerized into bioplastics (Encalada, et al., 2018). A representative case is Viber (case C02), the material is 100% biodegradable starch-based biopolymers, which are made from local waste and reinforced with miscanthus fiber. Their surface presents a unique fiberness with four different natural colors available, compatible with injection molding and compression molding (BIOPLASTICSHOP.NL, 2018). Chip[s] Board (case C01) has extensively tried to use bacteria from the dairy industry and various food wastes as raw materials for the microbial fermentation process to obtain organic acids for the production of Parblex® bioplastics. These microorganisms can produce bioplastic precursors, growing on various food waste streams. (BDC, 2016). The Parblex® has incredible surface glossiness and durability. It is suitable for injection molding, 3D printing, milling, and other industrial processing techniques and can be used in fields of consumer goods, fashion and interior design (Figure 20). In addition, some experiences have tried to add different fibers and other reinforcing materials to manipulate the performance of starch-based biopolymers in lab level (ÖZDAMAR and Murat, 2018). For example, increasing the use of canola pellets (compressed agglomerates from canola or sunflower waste) can improve the durability and strength of starch-based biopolymers; Moreover, changing the surface of polymer mold from metal to rubber will result in fewer cracks or deformations in the final material surface.

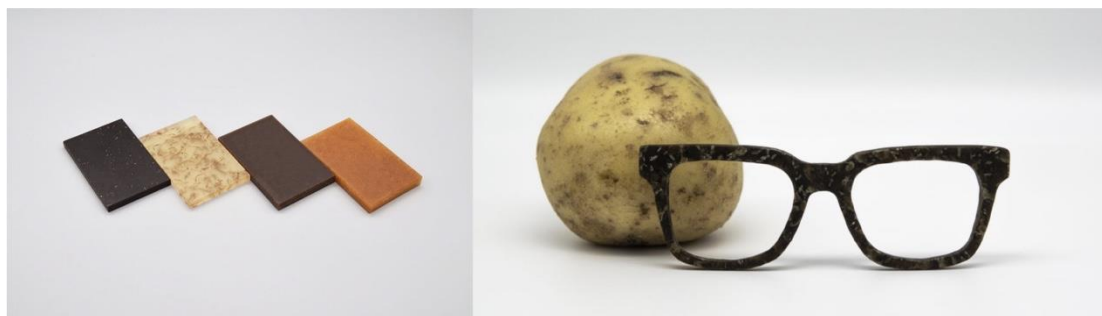


Figure 20 Bio-thermoplastic from potato waste (Left, Chip[s] Board), eyewear made by Parblex® bioplastic (Right)

Some designers attempt to obtain bio-based polymers from seafood waste (case C04, C09). A pioneering example is Shellworks (case C04), which extracted chitin from seafood shells, converted it into chitosan, and then into bioplastics. The prepared chitosan bioplastic film was used to develop a series of molding tools, such as machines for molding packaging. When the material reaches the end of its life, it can be reutilized as fertilizer (The Shellworks, 2019). Chitosan is easy to form a thin film and usually produces a material with a very high gas barrier property, which has been widely used in the production of edible coatings with antibacterial performance (case C09).

Other cases involve biopolymers obtained from mixed or uncommon waste sources, such as C03, C05, C06, C07, C08. Some of them are made into leather-like plastic for customized decorative accessories design (case C05), and some can be made into household products, such as cups, electronic product shells, etc. (case 03, 06). In addition, Pangaia (case 08) combined wildflowers with biomass plastics and injected aerogel to form a biodegradable down that can replace traditional polyester fibers, which can be used in various thermal insulation materials with warm, breathable, and hypoallergenic features.

2.3.4 Waste-based metal and other inorganic material

Material definition:

Recycled materials such as metal/glass/ceramics/rubber obtained from waste. For example, Bio-glass obtained from construction glass waste and Bio-Luminum tiles made from recycled aircraft aluminum (Coverings ETC, 2019).

Material manufacturing and Scope of application analysis:

Five kinds of materials are collected (Figure 21). The materials are mainly in the form of plates (case D01-05), used in construction, decoration, and household products. For example, the production of new tableware and utensils, which are sintered with ceramic fragments. (Fabrique Publique, 2020), and the manufacture of vulcanized composition rubber surface by Ecore, which are used for the floor surface.

Waste G.		Raw material (name/feedstock)	Developer/Year	Manufacturing (recycling method/scale/stock form)	Application
Metal / Glass / Ceramic / Rubber	D01	 Ecosurfaces / Rubber waste (Vulcanized Composition Rubber)	Ecosurfaces, USA / 2017	chemical recycling / Sheet,Tile  	 Rubber rolls and tiles / Rubber floors
	D02	 Bio-Glass / Post-consumer recycled glass from consumer bottles and industrial glass	COVERINGSETC, USA / 2010	Chemical recycling(sintering process) / Slab  	 Glass blank / Counters, Vanities, Back Splash, Walls, Shower Walls, Exterior Façade, Floors (R10), Industrial Design
	D03	 Bio-Luminum / Recycled aircraft aluminium	COVERINGSETC, USA / 2016	Chemical recycling(melting and cutting process) / Tile   	 Tiles / high-traffic flooring, high-end wall treatments
	D04	 TMF Valencia recycled glass / Glass waste(eg.discard window glass)	The Mosaic Factory, Netherlands / 2019	Chemical recycling / Tile  	 Tiles / Flooring
	D05	 Remake ceramics / Broken pieces of ceramics	Fabrique Publique, Netherlands / 2019	Chemical recycling / Slab   	 - / Consumer products (eg.tableware, vase)

Figure 21 Waste-based metal and other inorganic material case study

An interesting case is Bio-Luminum tiles (case D03), which are made from aviation aluminum obtained from scrap aircraft. With its high-strength nature, it is not easy to recycle them together with normal aluminum products. Coverings ETC melted the recycled aviation aluminum into blocks and then cut it into tiles. Since the energy used to recycle aircraft aluminum is only 5% of the energy used in the first-generation aluminum production process, the factory emissions are significantly reduced. In addition, thanks to its extraordinary strength and unique aging surface texture, this material can be used for high-traffic flooring or innovative wall treatments (as shown in Figure 22)

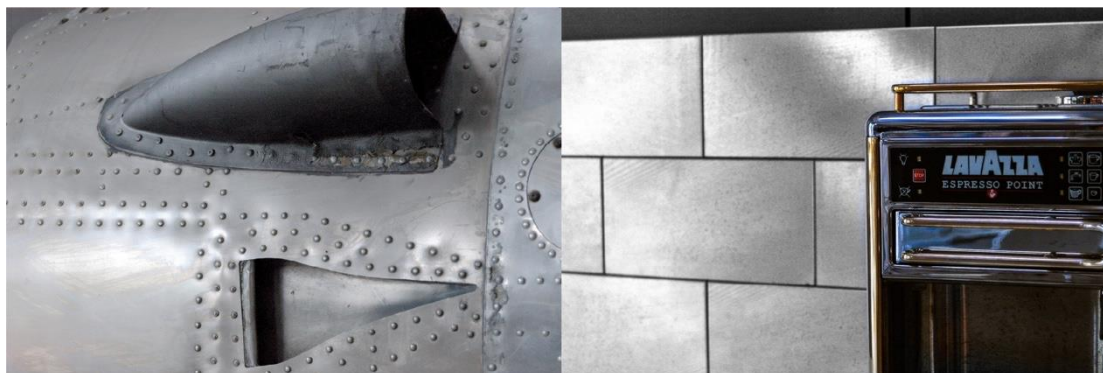


Figure 22 Aviation aluminum waste (Left), bio-Luminum tiles for wall treatment by Coverings ETC (Right)

2.3.5 Waste-based composite

Material definition:

Material formed by the combination of natural or synthetic reinforcement and natural or synthetic matrix, one of the matrix or reinforcement must be recovered from waste materials, such as wood shave + bio resin, coffee waste + natural binder, etc. According to whether the matrix is made by natural material, it is further divided into natural composite from waste and synthetic composite from waste. For example, wood shave + bio resin is natural composite from waste; graphite + bio resin is synthetic composite.

Material manufacturing and Scope of application analysis:

The case of composite materials is abundant (Figure 23). A considerable part of the composite materials is in the form of sheets and films, which are used in industrial products such as building materials, indoor space layout, and furniture surface decoration. Most of these recycled materials sources are construction waste and other inorganic materials, such as cement scraps in construction, shards of glass and ceramic waste, and ore mining derivatives, etc. (E01-E11). The main manufacturing processes involved are Bretonstone (also called vibro-compression vacuum technology), sintering process, consolidation process and casting process. There are also composite materials whose resources are by-products from production (eg. fiber residues, coffee grounds, wood chips, corks, rubber, and so on). Apart from being processed into sheets, they can also be made into soft materials such as fabrics and floor linings (case E12-E23), the main manufacturing processes involved are hot pressing, injection molding, adhesive.

























































































Waste G.		Raw material (name/feedstock)		Developer/Year	Manufacturing (recycling method/scale/stock form)		Application	
Composite	Synthetic Composite	E01		Ash-Grey Eco-Terr / Main stone waste mixed with cement, fly ash	COVERINGSETC, USA / 2010	Physical recycling (Bretonstone technology) / Slab  		Stone slab / Flooring, Outdoor Terrace, Pool, Pavers, Counters, Vanities, Walls, Exterior Facade, Furniture, Industrial Design
		E02		Eco-Cem / Main cement waste mixed with fly ash, Recycled wood pulp	COVERINGSETC, USA / 2010	Physical recycling (Bretonstone technology) / Sheet and Tile  		Tiles / flooring, interior/exterior cladding, furniture or worktops
		E03		OESTERPLAT / Marble and oyster shells waste, cement binder	D'WERKPLAATS, Netherlands / 2018	- / Slab and Tile  		Tiles / -
		E04		C-Slurry / Steel slag, lime mud, primary sludge from the wastewater treatment plant and wood dust in varying quantities	C-Hub & LiLinLab, Taiwan / 2019	Chemical recycling / Slab  		- / Wall construction
		E05		Circular Concrete Cityscapes / Waste from urban mining	Studio Wae , Netherlands / 2019	Chemical recycling / Tile  		Tiles / Surface treatment(eg.decoration) for wall or ceiling
		E06		Experimental Terrazzo / Waste material from construction(eg.brick/wood/metal etc.)	Huguet, Spain / 2019	Chemical recycling / Tile  		Tiles / Surface treatment(eg.decoration) for wall or ceiling
		E07		Stonethica / Waste from stone processings also in combination with heterogeneous materials, resin	Stonethica, Italy / 2018	Physical recycling(Bretonstone technology) / Slab and sheet  		Tiles / tiles and slabs, for use in both interior and exterior design schemes, Furniture board
		E08		Glass Form / recycled consumer glass and reclaimed eggshells	Steven Akoun, USA / 2010	Chemical recycling / Slab  		ACOUSTIC WALL TILES, humidifier, lamp, cup, knife sharpening whetstone, vases
		E09		SilicaStone / Glass and ceramics waste	Alusid, UK / 2018	- / Slab and Tile  		Tiles / tiles and slabs, for use in both interior and exterior design schemes
		E10		Eco-Gres / Unglazed porcelain (contains 36% pre-consumer recycled content)	COVERINGSETC, USA / 2010	Physical recycling(Bretonstone technology) / Tile  		Tiles / Tiles for wall
		E11		Zantech / Recovered graphite powder	Alisea , Italy / 2018	Chemical recycling / Powder  		Perpetua / Recycledge graphie waste
		E12		Corktex / High tenacity polyester thread, Cork waste, Tire waste	Corktex, Spain / 2017	- / Cloth, Sheet  		Fabric / lining floors, walls and ceilings
		E13		Spinneybeck's Beller Collection cork tiles / Industrial cork waste, resin	Spinneybeck, USA / 2019	Physical recycling / Slab   		Tiles / Surface treatment(eg.decoration/-sound absorption system) for wall or ceiling
		E14		013 Denim / Recycled denim yarn(from jeans waste), organic cotton yarn	Wolkat, Netherlands / 2017	Physical recycling / Cloth  		Textile / Denim fabric for garments, shoes, bags
		E15		Jeans on the wall, Textile on the wall / Textile waste(eg.recycled jeans fibers) or biobased textile fibers, Biobased glue	Denimtex, Netherlands / 2017	Physical recycling / Paste  		Textile plaster / Surface treatment(eg.-decoration) for wall or ceiling
		E16		denim fiber-based panel material / denim fibers	PLSTCT, Netherlands / 2019	chemical recycling / Panel  		Modular partition blocks / Desktop partition
		E17		Tire Veneer / Rubber waste(buffings) from tire renovation, Virgin EPDM rubber granules , Urethane binder	YEMM & HART, USA / 2005	Chemical recycling(compression molding) / Layer  		Tire Veneer / flooring material, consumer products, vibration dampeners and furniture surfaces, sports & recreation, animal housing, Cargo & Truck Mats
		E18		Sustorable engineered stone / PET bottles	Sustorable, Spain / 2014	Chemical recycling / Sheet  		Customized sheet / desktop, partition, wall surface treatment
		E19		Recycrom / textile fibres from used clothing and manufacturing waste	Denimtex, Germany / 2017	Chemical recycling / Powder  		Dyes / dye for fabrics and garments made of cotton, wool, nylon or any natural fibre and blend.
	Natural Composite	E20		That's Caffeine / waste coffee grounds, bio-resin	Atticus Durnell, UK / -	- / Sheet  		Lighting, vase and other consumer products
		E21		LOZI / sawdust, bio-resin	LOZI, UK / 2010	Physical recycling / Pasta  		Table top
		E22		Tableware from wild leaf / fallen Indian areca palm leaves, resin	Wild life, USA / 2019	Physical recycling (compression moulding) / Slab  		Tiles / Surface treatment(eg.decoration/sound absorption system) for wall or ceiling
		E23		Flash line / 100% recycled yarn and contains 86% recycled and biobased materials	Interface , Netherland / 2021	- / Tile  		Tiles / Carpet tile

Figure 23 Waste-based composite material case study

The Bretonstone can turn stone waste into non-porous and very stable artificial stone slabs. In detail, firstly, mix milled stone waste and other types of stone materials with unsaturated polyester resins to obtain a mixture to inject into molds. Second, vacuum the air and catalyze the molded product while vibrating and applying pressure to the mixture. When the mixture is heated and formed, the product can be taken out. Moreover, specific technical and aesthetic requirements can be achieved by manipulating the stone aggregate content (Breton, 2019). A representative case is Stonethica (case E07), the company uses resin to combine marble waste and natural stones to produce slabs. The unique texture of the marble fragments is used to form luxurious artificial stone slabs with smooth and moisture-resistant surfaces. These slabs can be applied to floors, walls, kitchen counters, bathrooms, and Interior design (Figure 24). Post-processing is no different from traditional marble. It can be cut and carved. By adding siliceous stone and other auxiliary materials, the final slabs can acquire the same hardness as granite, with excellent performance and customizability (Stonethica, 2019).



Figure 24 Marble waste collection (Left), Stonethica used for interior design (Right)

The sintering process is mainly for mixed waste materials from glass and ceramics. Like the case E09. Alusid mixed discarded pre-consumer glass, ceramic fragments with different minerals to create a series of tiles and solid surfaces with handmade quality, bright glaze and imperfection stone texture. These ceramic tiles and concrete surfaces can be used for tabletops, wall coverings, and construction surfaces. A variety of subtle colors, shapes, and textures can be selected. The low-temperature firing process results in lower energy consumption than primary ceramic processing (Alusid, 2021).

For other cases, it is more exploratory. For example, Steven Akoun (case E08) was inspired by the characteristics of glass foam generated from glass shards. He added different mineral foaming agents for firing to obtain a material with varying levels of expansion and porosity. Due to the material's outstanding traits at good sound absorption properties, light transmission, heat insulation, and water absorption, it is used to produce sound-absorbing panels, lamps, coffee cups, humidifiers, and other daily necessities (Steven Akoun, 2018) (Figure 25). In the cases of E03 and E06, they tried to mix different wastes into waste stone slabs (such as terrazzo) through cement to refurbish its functional performance. Through the color palette contrast, the embellishment materials have been strengthened, and form unique aesthetic quality, see Figure 26 (OESTERPLAT, 2018; HuguetxApt, 2019).



Figure 25 Material exploration samples(Left), knife sharpening whetstone with three sharpening level by Steven Akoun (Right)



Figure 26 Huguet X Apt, experimental terrazzo for furniture

Waste fiber, cork pellets, rubber, and other production waste can be mixed with resin or other polymer-based materials to make fabrics, soft veneers, and panels used in construction, soft decoration materials, or other industrial products. For example, boards and fabrics made from waste denim fibers mixed with bio-resin (case E14, E15, E16)(Fig 2.20). Jean on the wall (case E15) encourages recycling all waste textiles into fibers and mixes them with resin to form environmentally friendly wallpaper coatings to be used for wall treatment. They released the red and blue denim wallpaper series and other unique textures through the coordination of different fiber thicknesses and colors (Denimtex, 2017). PLSTCT (case E16) makes a lightweight sound-absorbing panel material with high strength and stone-like beauty without losing the warm and soft touch of textiles. It is a high-strength fiberboard made by only water, heat, fiber, and pressure, and the material is degradable and does not require the addition of chemical components (PLSTCT, 2020).



Figure 27 DENIMX uprecycling process of jean waste (Left), Motorcycle exterior design by DENIMX (Right)

Cork particles can be obtained in large quantities from cork manufacturing. Due to its low thermal conductivity and reasonable compressive strength of cork, the composite made of the cork granules can be used in floor coverings, handles, and other anti-skid scenes (Gil, 2009). For example, Corktex carpet linings manufacturing (case E12): Firstly, mixing the cork particles and rubber into rolls to obtain mats. Then heating and polymerizing them in the mold to obtain cylindrical blanks. Finally, cutting the blanks into cork-rubber mixed sheets for Corktex carpet back material. The floor or ceiling materials made of Corktex back material possess high level of sound insulation, heat insulation, non-slip and comfortable, which can be used in public places such as hotels (Corktex, 2020). In addition, composite materials mixed with cork particles and other waste (such as packaging paper) can be used to make acoustic panels, furniture, and other molded industrial products (case E13). The mixture is directly heated to complete agglomeration and achieve excellent mechanical strength (Spinneybeck, 2019) (Figure 28).

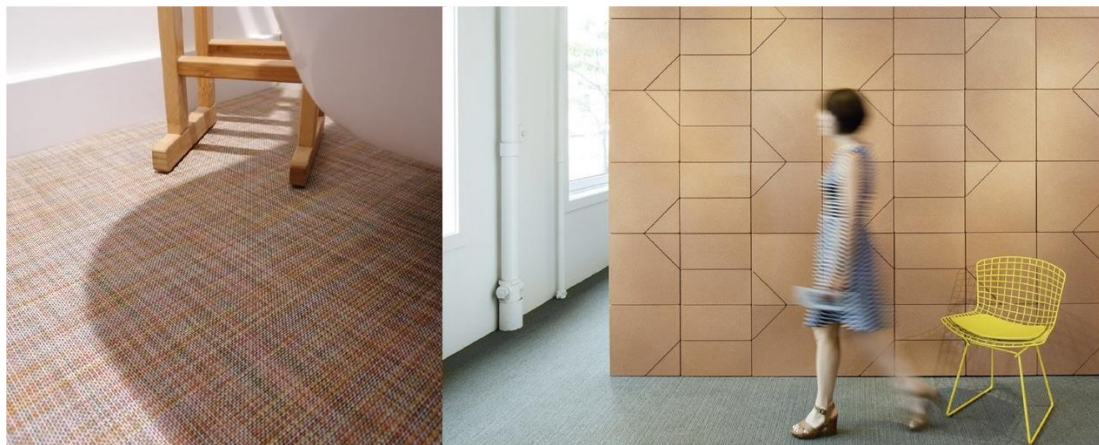


Figure 28 Corktex carpet (Left), Lisboa acoustically absorptive composite cork wall system by Lars Beller Fjetland (Right)

Other cases involve mixing resins with wood chips, plant leaves, coffee grounds, and other by-products or using these waste as fillers for low environmental impact. For example, Flash line (case E23) uses recycled bio-based materials as a backboard with a special turfing processing technique to achieve a negative carbon emission carpet; Wildlife used waste of Indian palm

leaf with resin to make plates by hot pressing. LOZI, whereas, explored the combination of sawdust and bio-resin as the aesthetic quality of the furniture surface. (Flashline, 2021; Wildlife, 2019; LOZI, 2020)

2.3.6 Analysis of the potential of recycled materials in product design and answer for Q2

In conclusion, among 69 recycled materials, used in construction and interior design accounted for as much as 37%. The main product types are functional panels, patches, tiles, and carpets. Secondly, household products account for 20% (Figure 29). The products involved include tableware, glasses, accessories, toiletry products, pencils and other daily necessities, as well as humidifiers, table lamps and other household appliances. Textiles account for 18%. In addition to clothing and footwear application, material also used in the surface treatment of furniture. Packaging and disposable products accounted for 10%, furniture and others accounted for 9% and 4%, respectively. Materials directly processed into specific products account for 59%, and the raw materials are usually kept secret or directly completed by handcraft. 41% material cases are released in the form of raw materials. These materials can be obtained and flexibly applied to different project requirements, usually in the form of cooperation between product developers and raw material vendors.

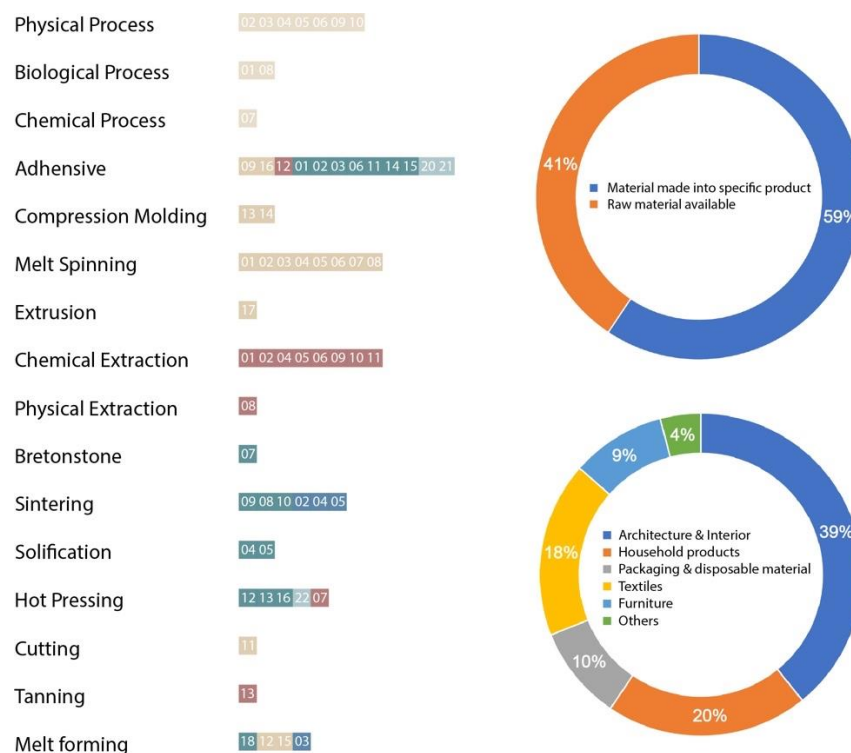


Figure 29 Manufacturing Process and Application Analysis - Materials from Case Study

In light of the above studies of recycled material cases reviewed in this paper, 6 advantages of using recyclates in product design can be summarized.

1. Innovation potential

Unlike traditional materials, the sources of recycled materials are very abundant and relatively

new. Moreover, designers and related practitioners can further intervene in selecting material sources, processing and even production methods, carrying out different levels of material tinkering according to project requirements so that materials can derive multiple application possibilities. These abilities expand the variety of product solutions and facilitate the innovation of new products (case A04, A07, A10, B11, C05, D03, E08, E21, etc.).

A prominent example is case 08. Steven Akoun explored a series of glass foams with different densities by controlling the quantity of mineral foaming agents. He took advantage of the water storage property and good evaporation structure of this material to fulfill the integration of traditional humidifier components (water storage tank and evaporation module). Other experimental samples with high-density are used for the manufacture of whetstones (Steven Akoun, 2018)

2.Promotion of product customization applications

Product customization can encourage clients to participate in the development of the purchased products, that is, to become a co-designer so as to obtain products that more closely meet their needs. Furthermore, the manufacturing flexibility and design orientation of recycled materials also promote this behavior (case A02, A07, A08, B02, B05, C05, D05, E07, etc.).

For example, Denimtex (case E15) collects and recycles waste textiles materials provided by clients into wallpaper coatings with unique symbol meanings to meet the specific decorative needs of clients. A similar approach is also used by Organoid (case A07). With coffee waste provided by users, the company produced high-density laminates with cocoa bean texture on the surface and applied them to the interior decoration of customers' flagship stores.

3.Traditional materials alternatives

Recycled materials have the potential to replace traditional materials in terms of manufacturability, functionality, and sustainability.

For example, the Qmilk fabric (case A01) obtained from spoiled milk can be used as a substitute for cotton. The products made of Qmilk show the natural antibacterial effect, thanks to the amino acid composition in the protein-based fabric. In addition, this material is the only natural fiber with thermalbonding properties. It has the characteristics of non-woven fabric processing and can achieve high-efficiency production. It does not require conventional plastics or phenolic resins to bond with other fibers, so the structure is light, and the material is 100% compostable. Govaplast used PE-PP recycled plastics in outdoor public facilities since they have better cleanability and durability than wood and concrete.

4. Low environmental impact

The above studied cases review three eco-friendly advantages of using recycled materials over traditional materials, including: reducing the use of primary materials; low emissions in the manufacturing process; reducing the environmental impact caused by low-level treatment methods such as landfills.

The specific implementation methods related to products can be divided into 4 types:

1) Replace primary materials with recycled materials. For example, Flashline (case E23) invents first negative carbon emission carpets by using recycled bio-based materials as linings combined with their turfing technique.

2) Low-addition, low-energy manufacturing process (case A01, A08, B01, B11, D03, E09, E23, etc.). For example, Alusid used a low-temperature firing process to convert waste glass into tiles, leading to a lower processing energy consumption compared with original process.

3) Refurbishment of materials (products). For example, Huguet successfully avoided the fate of waste stone-made sinks being landfilled. They mixed other wastes into abandoned sinks through cement and cooperated with designers to create a unique aesthetic quality of recycled products on their surface. The work triggered thinking about the relationship between value, sustainable quality, and inheritance.

4) Closed-loop material-production system (case C04, A08, D01, E07, etc.). For example, DenimX created the circular uprecycling process of denim fiber waste. The products designed by them (e.g., DenimX Suitcase, chair, etc.) can reenter the initial material flow when it reaches its service life.

5. Bring unique aesthetic quality and novel interactive experience

Aesthetic quality can be understood as the degree of pleasure obtained from sensory perception (Hekkert, 2006). Some studies point out that visual and tactile perception are the most effective ways we experience product characteristics (Schifferstein & Cleiren, 2005), and the properties of materials that make up the products are the basis for building these experiences (Karana et al., 2013, p. 16). These characteristics, through their influence on different sensory channels, encourage different senses to work together to create different user experiences (Karana et al., 2013, p. 19). For example, Organoid uses wildflower waste to produce decorative board, the unique plant scent and neutral soft color remaining on the surface make users feel the sense of being accompanied by nature. Here we choose the three material characteristics (color, material appearance quality, and tactile quality) that can most affect the visual and tactile senses to analyze the unique aesthetic quality of recycled materials.

Regarding the color, some recycled materials maintain their simple, elegant, and blank style, making them as similar to the virgin materials as possible (such as Orange fiber, Qmilk, etc.). Keeping their blank color offers relatively more freedom for designers to perform surface treatment at a later time. However, most materials have specific aesthetic qualities, depending on the characteristics of the waste and the processing techniques. For example, Viber (case C02), due to containing miscanthus reinforcement fiber, presents the features of low saturation and has a slight fiber texture, which suggests naturalness and gentility to users. Materials with similar quality include case A11, A14, B13, C06, D05, E13, E20, etc. However, by biological dyes and other surface treatments, recycled materials with a richer color range can also be achieved, such as case A06, B16, C01, D04, E21, E23, etc.

Regarding the visual quality, some recycled materials retain the unique aesthetic quality, which is of the original waste, as a result of milder manufacturing processes, such as Fish skin leather (case A13), Organiod (case A07), Freitag (case B11), Stonethica (case E07), etc. Other materials can be regarded as having deeper processing, and it is usually difficult to recognize the features of the original waste of which the materials are made, such as case A01, A09, A14, B08, B13, C05, D01, E09, E14, etc. Some studies believe that recycled materials have certain imperfections, such as aging texture, wear marks, etc.. It is different from the perfect aesthetics, which industrially manufactured products pursue, bring people a unique product experience, sense of value, functional and aesthetic sustainability (Rognoli & Karana, 2014). This is due to the heterogeneous structure of the material surface usually with different colors or inclusions, and people's response to the dominant perfectionist technology (Ramakers, 2002). Undeniably, there is the phenomenon of changes from perfection to imperfection in those cases. For example, the surface of case C05, E06, E09, B15, B16 presents a large degree of uncertainty, defects, which are mainly derived from hand-processed waste materials or glass, ceramics waste, etc. The imperfections of cases A06, C02, C06, E15, E17, etc., are significantly controlled within the scope of the standards, and most of them are commercial materials. Being used as commercial materials also demonstrates that the imperfection of materials is gradually being accepted in commercial design (e.g., case D01, E20, etc.).

The tactile of recycled materials depends on which wastes are mixed in the final material. The recycled materials, which mainly consist of inorganic materials such as construction waste, are tough and cold to the touch (e.g., case E01-E10, D02-05). However, other types of materials are mostly soft, mild, and some materials made of rubber waste have good resilience (e.g., case D01, E12, E17).

The difference between the aesthetic properties of recycled materials and traditional industrial materials should be more discussed (for example, which recycled materials have a suggestion of naturalness, etc.) (Rognoli & Karana, 2014; Bramston & Maycroft, 2014). These unique characteristics of recycled materials are what traditional materials do not possess and their exceptional competitiveness for product design.

The surface characteristics of recycled materials can provide users with a pleasant interactive experience (e.g., case A04, E15, E21, etc.). A representative case is Night Lamp by Steven Akoun. A series of bulb-like objects with different transparency, color, and shape by adding a glass foam powder mixture to ordinary blown glass were obtained. The last one, a finished product, possesses a mottled and semi-transparent texture on the surface, which simulates the soft light of sunset and the starlight shining effect, bringing users an exquisite lighting experience (as shown in the Figure 30).



Figure 30 Blowing experiment samples (Left), final product, an emotional night lamp (Right)

Chapter 3 Material Selection Study in Product Design

3.1 Product Material Selection Study in Academic Context

3.1.1 Study background and purpose

One of the important tasks of a product designer is material selection. In the face of more and more available new materials, it is not easy to balance their respective characteristics, applications, advantages, and disadvantages to select the most suitable material (Veelaert et al., 2016). This requires us to set appropriate screening indicators according to a series of product application requirements to complete (Ashby et al., 2007, p.36). Materials selection aims to transform the products' specifications, requirements, intentions and design drivers into a list of required material properties, in order to be able to find a corresponding material (Veelaert et al., 2016). In the process of selecting the best material, product designers or engineers need to consider a series of important criteria and attributes, namely "factors that affect the selection of materials for a given application" (Rao & Davim, 2008, p.751), for example, to design an outdoor seat that brings warm experience to user, designers need to consider material technical and sensorial factors. Therefore, oak may be one of the candidate materials due to its low thermal conductivity and surface warm color⁹. Academia has done in-depth research on the selection factors of material technical aspects, such as mechanical attributes, material manufacturability, etc.(Chiner 1988; Farag 2002; Ashby et al., 2007), and recent research has begun to explore the sensorial properties, meanings and other user interaction aspects of material (Rognoli, 2010; Karana, 2010; Kesteren, 2007). Predeville (2014) organized these factors that affect material selection from existing literature, showed in Figure 31

Ashby and Johnson 2003	Van Kesteren, 2008	Karana et al., 2008	Peças et al., 2012	Ogunkah and Yang 2012
- Technical	- Process properties	- Technical	- Technical	- Technical factors
- Economic	- Material properties, Sensorial properties	- Manufacturability	- Economic	- Cost/Economic factors
- Sustainability	- Geometric properties	- Economic properties	- Sustainability	- Sensorial factors
- Perceptions/ Intentions		- Sensorial properties, Ecological properties	- Environmental	- Environmental/Health factors
		- Intangible properties		

Figure 31 Pre-conditions influencing material selection (Predeville, 2014)

Based on various material selection factors, there are mature material selection methods and corresponding databases to support product engineers to select suitable materials. Recently, there have been resources to support material selection in design-related factors, such as

⁹ According to modeling aesthetic attributes by Ashby, whether a material feels warm to the touch depends on the density, thermal conductivity and specific heat capacity of the material (Ashby & Johnson, 2013, p.218). However, the actual physical properties of the material do not always match the sensory properties (Rognoli, 2010). For example, a dark-colored wenge may bring a colder experience compared to light-colored willow even if their tactile temperature is almost the same.

inspiration material database represented by Design insite, etc. (Figure 32: Overview of existing resources for material selection by Veelaert, 2016).

	Information	Inspiration
Software & Database	CES Selector	Design Insite
	CAMPUS Plastics	Materia, Materio
	MatWeb	Material Connexion
	CES Products, Materials and Processes	
Tools & Methods	Ashby charts	Material Driven Design (MDD), MOM
	Material Selection Activities (MSA)	Material in product selection (MiPS)

Figure 32 Overview of existing resources for material selection (Veelaert, 2016)

This section will review relevant method and resources that support designers to complete material selection from an academic perspective. According to collected literature about material selection in design sector, four types of material selection activities will be discussed: Material selection in product design (Ashby & Johnson, 2013), Material in product selection (MiPS) (Kesteren et al., 2007), the Meaning driven material selection tool (Karana, 2010), and Material driven design (MDD) (Karana et al., 2015). The purpose of this part study is answering following questions:

- ***Q1) What material selection factors and what kind of material information do the different material selection activities reflect that product designers need to consider? (selection factors and content study)***
- ***Q2) How is this material information obtained and what methods/database are considered for the different selection activities? (selection process study)***
- ***Q3) Which participants need to be involved for the different material selection activities? How do the methods/database under different material selection activities encourage design-related material selection? (selection interaction form study)***

The answers to the above questions have important reference significance for the ultimate goal of this thesis – building a recycled material database for product design. These selection activities reflect the material information sought by the designer and how to communicate and interact with design-related material resources. These findings provide design support for the organization and display form of recycled materials in the database.

3.1.2 Material selection for product design (Ashby & Johnson, 2013)

Selection methods/database

Providing a basic structure of a three-step method to cope with material selection challenge: Identification – Material Selection – Implications. The first step is identification: determining the design requirements about the material, clarifying the material constraints and objectives, expressing it in a quantitative or qualitative manner, and finally clearly defining the material limit or material index/features needed. Step two is material selection: a screening process based on the materials that meet the conditions proposed in step one. Four types of selection

methods are proposed, namely analysis, synthesis, similarity and inspiration. They can be flexibly combined to meet the various material selection requirements, detailed explanations are given below. Step three is implications: determining other aspects of the selected material from step two, such as manufacturability, cost, etc., and comprehensively considering to select the optimal material.

Analysis

Through analysis method, candidate materials that meet a series of technical requirements are screened out. The analysis method usually faces the material selection requirements of the product's function/engineering. The realization process is as follows: first, clarifying the product functional requirements, translating the requirements into objectives and constraints that the design must meet, determining the material performance indicators, and screening in the CES database to identify candidate materials. (Ashby et al., 2007, p.36).

Synthesis

Choosing a material based on its foundations in previous experience and analogy. Usually the selection requirement is to find materials with certain intentions, aesthetics or perception characteristics, such as material selection for a certain medical device for the treatment of children's diseases, hoping that the materials can bring them feeling of playful and lively so as to relieve children's fear of the treatment process. So, an idea based on the synthesis method can be acquiring inspiration from materials of entertainment product design for children.

Similarity

By considering similar materials to replace existing materials, this method is a good way to promote designer away from pre-conception materials and have a look about new alternative materials. The specific approach is to use previous material requirements but relax some non-critical restrictions, then more potential candidate materials can be checked (Ashby & Johnson 2013, p.136).

Inspiration

The material solution inspired by designer living environment and creative activities, such as ideas from combination of certain magazines, passing glances in their daily life and other random experiences around designers (Ashby & Johnson 2013, p.137).

In addition to the material selection method, a material resource library to help designers cope with material selection in the design field is developed (Figure 33) — Products, Materials and Processes database, Granta 2016 (Ashby & Johnson 2013, p. 132). The database considers the classification of information for product design and meets different material retrieval purpose for design aspects. Six types of data are recognized as described below, the detailed information diagram is shown in Figure 34

Products: contains factual data for product attributes eg.the product name, manufacturer, model number, price, and details of performance etc.

Materials: the specific materials used to make the product eg.stainless steel, ABS etc.

Processes: processing technology of production products eg.injection molding, punching etc.

Aesthetics: five senses embodied by product, the visual, tactile, acoustic, olfactory and taste attributes. Then, nine specific aesthetics attributes are introduced to better quantify sensory characteristics: tactile warmth, touch, pitch, tone, flex, resilience, scratch, resistance, light but stiff, light but strong.

Perceptions: It represents the feeling that the product brings to people, eg.the mouse looks cute. Different from the above data, this is subjective and will vary according to different context, such as, culture, taste, and fashion etc.

Intentions: this data describes what the product is meant to be – the priorities in the mind of the designer, such as ‘design for mass production’, ‘design for recycling’, etc.. It usually comes from design requirements and different products may show similar intention, eg.smart phone or hearing aid for old, the intention of these two products is ‘design for the elderly’.

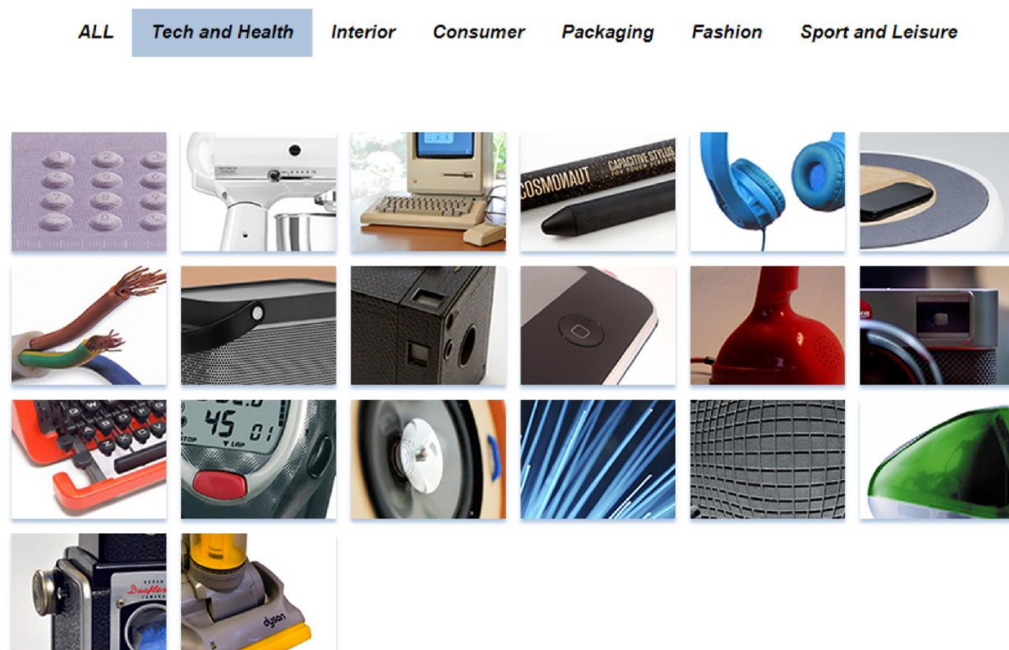


Figure 33 Products, Materials and Processes database (Granta 2016)

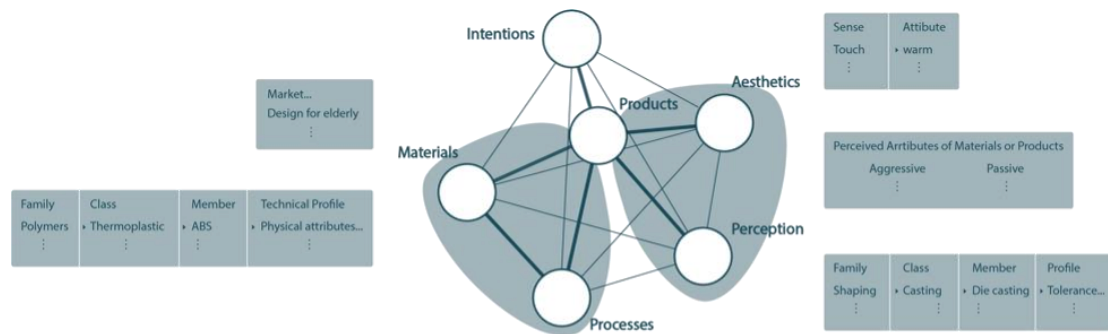


Figure 34 Information classification about product design (Ashby, 2013)

Selection factors and content

In product design, four dimensions of information about materials should be considered: engineering, usability, environmental, aesthetics and personality, and the three types of material attributes involved: technical, aesthetic, ecological (Ashby & Johnson 2013, p.63-95).

The engineering dimension considers that the product can work, and the material technical attributes and processability are the key elements to achieve this requirement; the usability dimension proposes that the product is easy to use, where technical attributes and aesthetic attributes play a role at the same time, such as the material of light-emitting diode indicators used in complex equipment needs to be emphasized in color and brightness in order to reduce misreading rate and improve readability. The environmental dimension considers that products meet the sustainability requirements of manufacturers or consumers, involving the ecological and technical attributes of materials. Aesthetics and personality dimensions consider the emotional connection between the product and the user, the aesthetic attributes and hidden aspects for specific materials¹⁰ play an important role here.

Interactive way of selection

Participants: product designers, product engineers

Interaction form: The Products, Materials and Processes database supports simple and in-depth retrieval of material/product information. Designers can use the database to obtain well-designed product cases to obtain information about the use of materials, manufacturing knowledge, design styles and other design elements. Providing different data to meet designers and engineer needs about material selection. The database contains engineer's and designer's views on material information which can promote internal communication between designers and engineers.

3.1.3 Material in product selection (MiPS) (Kesteren, 2008)

Selection methods and database

Product Material Selection (MiPS) technique was proposed by Van Kesteren (2008) to help

¹⁰ hidden aspects for specific material means material perceived attributes, similar to perceived attributes and associations from products, a certain material evokes the feeling of..., for example, the effect of wood finishing on the surface of a certain product evokes the association of handicraft quality.(Ashby & Johnson 2013, p.89)

product designers and clients to define the sensorial properties of materials required for desired user interaction (Figure 35-different tools presented in MiPS technique). The selection process consists of three steps, definition – translation – usage.

Definition step

This step requires the designer and the client determine the sensorial aspects that should be considered in the realization of a certain product user-interaction aspects (for example, if the designed product needs to bring people a friendly and durable experience, which sensorial aspects can be determined?). For this step, Kesteren developed three communication tools to assist designers determine the sensorial aspects: pictures, samples and question tools, focusing on different aspects of user-interaction, allowing clients to participate in the discussion and determining what the material-related user-interaction aspects are. The picture tool is based on designers who provide clients with images with certain product personality to communicate with each other the feelings of products that they want to convey to users. Designers could use client feedback and presented images to obtain material sensorial inspiration for creating desired user-interactions; The sample tool is used to further define the material profile. The designer or client can select a combination of material samples representing a certain personality from a sample group of different sensory properties; The question tool is used to help designers consider the sensorial interaction between the user and the product (for example, when the user unwraps the product, which positive sensorial experiences are evoked?), this tool includes a question list and a sensorial property checklist to help designers translate the collected sensorial aspects into sensory properties.

Translation step

Translating the sensorial aspects of user-interaction obtained in the previous step into the physical properties of the material (here you can use the relation sheet for sensorial and physical properties to complete the translation), and combining the design requirements of other aspects of the material (such as cost, manufacturing, environmental requirements, etc.)), and finally identify the complete material requirements of the project.

Usage step

In the search step, the product designer uses the sensorial and physical properties obtained in the above steps, combined with the overall needs of the project to form a complete material selection standard, and combines material databases and other related resources for material selection.

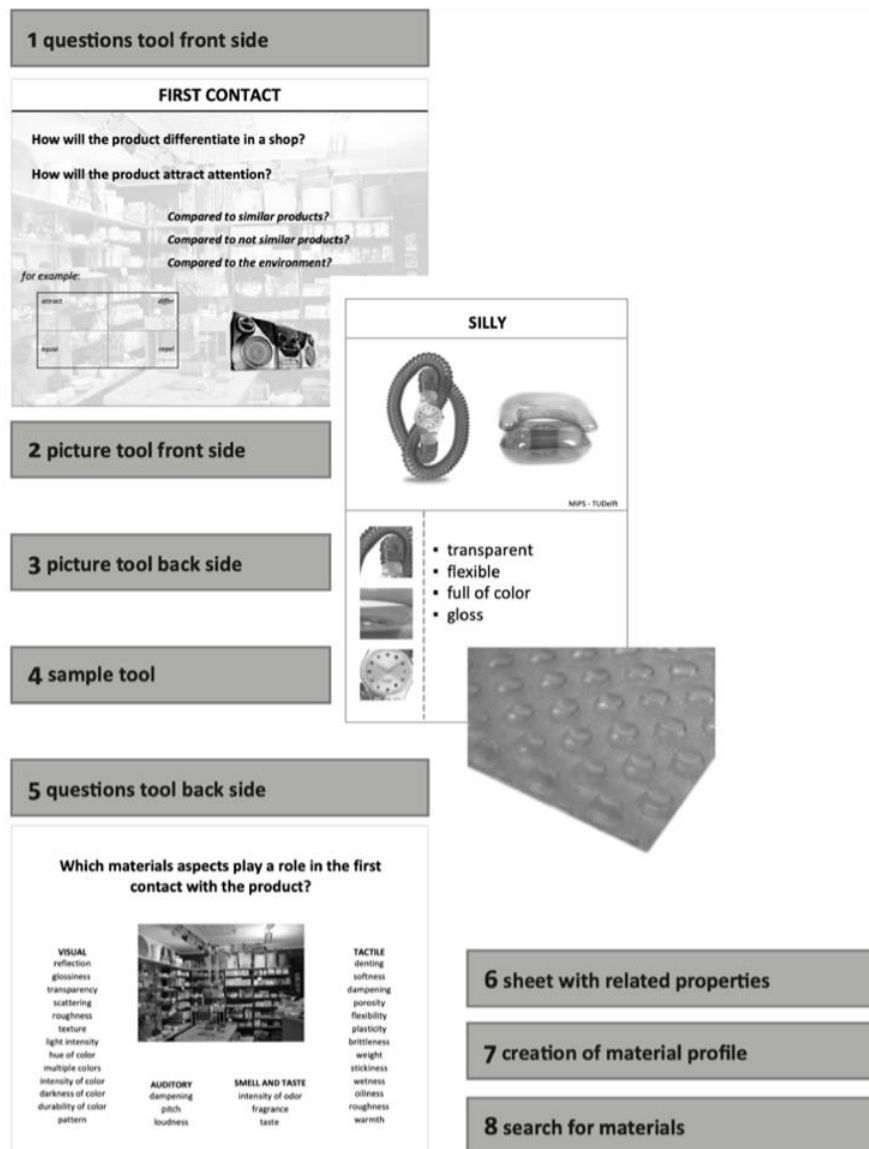


Figure 35 Different tools presentation in MiPS technique, 1-5 are performed in the definition step, 6-7 in the translation step, 8 in the usage step (Kesteren, 2008)

Selection factors and content

Focusing on user-interaction aspects of materials. It is the material aspect that affects the use and experience of the product. For example, gloss affects the effect you read from the display (in terms of usage), and color is a very important aspect that affects the product experience. (Kesteren, 2007)

Considering two types of material properties: sensorial properties and physical properties. Sensory properties are material properties that can be perceived by one of the five senses. Examples of these properties are hardness, thermal conductivity, color, optical quality, texture, tone, and smell, etc. The physical properties describe the technical characteristics of the material. It includes mechanical, thermal, electrical, and optical properties, etc. which are usually presented in numbers (Ashby, 1999).

Interactive way of selection

Participants: designers, clients, users (not involved, but considered), experts, manufacturers and material suppliers

Interactive form: designers and clients discuss the product/material images and samples to form a common understanding of expected sensorial aspects; internal discussions between designers determine the sensorial properties that dominate product user-interaction aspects; communicating with materials experts to obtain professional advice.

3.1.4 Meaning driven material selection (Karana, 2009)

Selection methods and database

Material should not only satisfy the function, but also attract the user's feeling and help convey the intended meaning of the product. This method is based on the Meanings of Materials (MoM) model (Karana, 2009). This model consider the meaning of a material as a relational concept in which material, product and user are jointly effective, a set of related aspects are identified and tested in a series of studies, such as sensorial properties, manufacturing processes, product shape, function, gender, age, expertise and culture (Figure 37). The key to the concept is to state a series of combined material properties will evoke unique meanings when facing a specific user in a certain situation. Therefore choosing a material that can create a certain meaning requires not only considering its material characteristics, but also identifying other related elements and context involved. This method help designers identify and create this pattern to recognize the specific meaning of materials, finally getting material selection solution that conveys a specific meaning. The method implementation is completed in 3 steps, defining intention, data collection, result analysis.

Defining intention

determining the expected meaning of material with target group, eg. How to reflect sexy to Asian female through materials.

Data collection

First let the target user select a material that they think has the expected meaning, provide a complete visual picture, or a part of the product. Then, according to sensorial scales or questionnaire method to evaluate sensorial properties of material they selected (Figure 36).

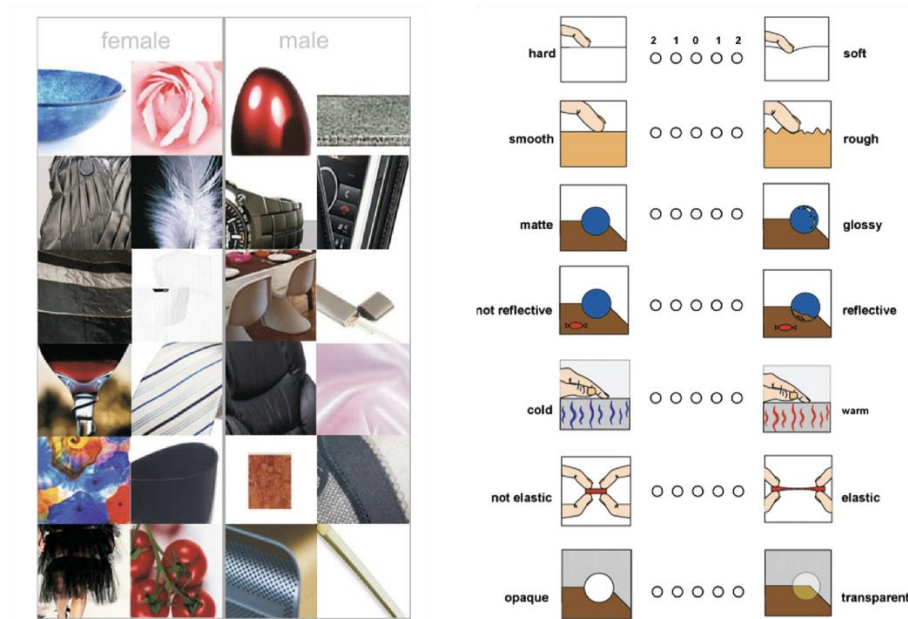


Figure 36 Sexy materials selected by 12 female and 12 male participants (left), Sensorial scales (right)

Result analysis

According to the pictures, explanations, and sensorial scale evaluation results generated by users, it is possible to determine the similarities and differences of sensorial properties that different groups of people pay attention to the meaning of specific materials, and combine the factors considered in the Meanings of Materials (MoM) Model to assist designers to determine evoked pattern of expected material meaning, identifying the material properties that play a key role in giving the intended meaning.

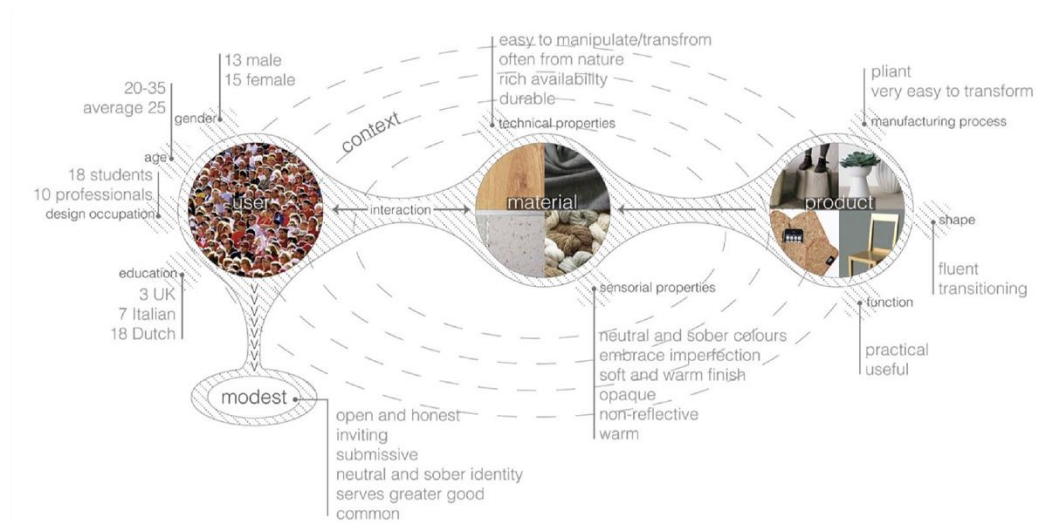
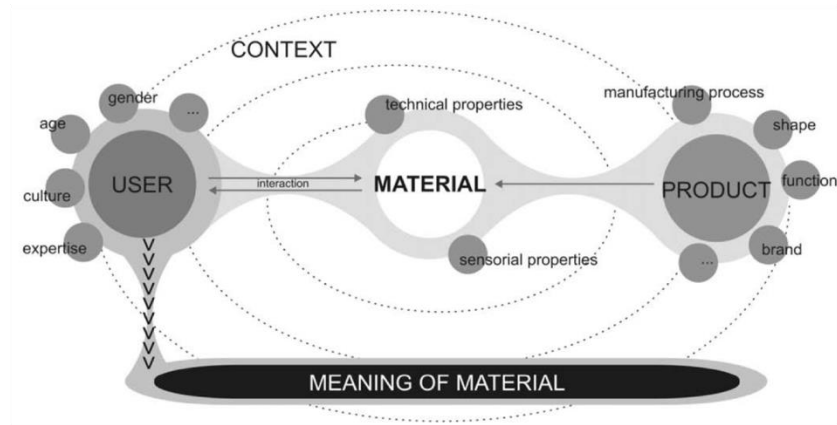


Figure 37 The meanings of Materials Model(above), Visualisation of modest based on The Meanings of Materials Model(below) (Karana, 2009)

In addition, an online database on the meaning of materials has been developed. It is an interactive tool that allows designers to browse selected materials and the conditions for the evoked pattern of specific meanings based on Meanings of Materials (MoM) Model, as shown in the Figure 38.

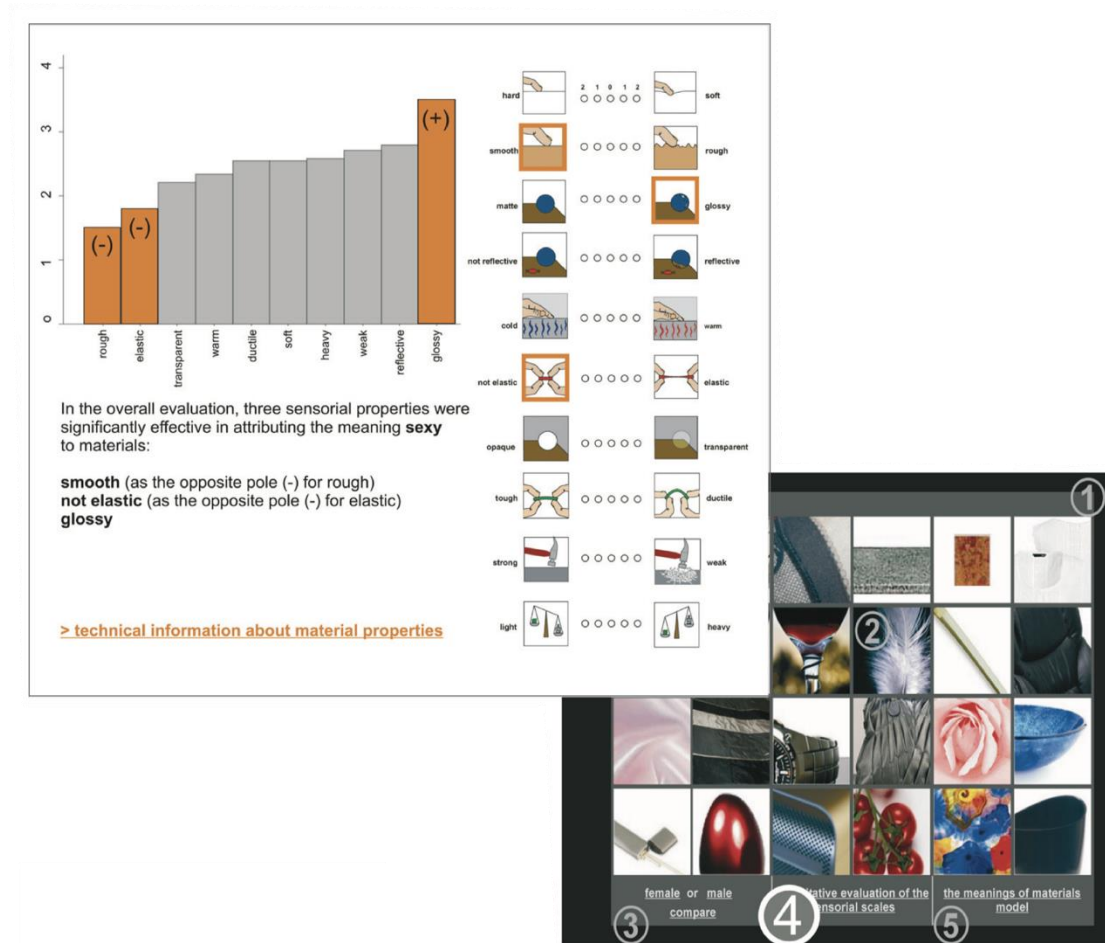


Figure 38 One of the interface of this tool: quantitative evaluation of the sensorial scales page. Three sensorial properties of materials that contribute to the meaning of sexy are identified: smooth, not elastic, and glossy.

Selection factors and content

The meaning aspects of material: a series of combined material properties will evoke unique meanings when facing a specific user in a certain situation, eg. The professionalism meaning of the product can be achieved through its luster, firmness and smoothness and the sharp geometric shape of the product, therefore the aesthetics of the material and product shape together achieve this meaning.

The components that form the meaning of the material: Material (contains technical properties and sensorial properties); Product (contains manufacturing process, shape, function, brand etc.) User (contains gender, age, culture, expertise etc.)

Interactive way of selection

Participants: designer, user

Interactive form: navigating in collages inspires designers' ideas of expressing meaning by materials. The database supports the exploration of the meaning of the material for a specific group of people. The important sensorial properties related to the meaning can be determined through the specific group filter and the corresponding sensorial scale comparison page,

linking with the technical properties chart. The Meaning of materials model module helps designers gain insight into other critical components that affect the meaning of materials.

3.1.5 Material driven design (MDD) (Karana et al., 2015)

Selection methods and database

Developed by Elvin Karana and Valentina Rognoli etc. (2015), this method support designers to define and design meaningful experiences and use materials at hand. Considering three types of materials: well-known material (traditional materials that have been widely used), unknown material (there are complete samples but not widely used, such as thermochromic material), material proposal with semi-developed or exploratory samples(experimental material, such as material based on coffee ground). The method consists of 4 steps (Figure 39: MDD method framework and application cases).

Understanding the material

This step guides the designer understand the technical characteristics of the material at hand, as well as the experimental characteristics. Through tinkering experiments, user studies, material benchmarking to better understand the material inherent qualities, limitations and potential application areas in product design. Tinkering are mainly for relatively unknown materials (such as experimental materials, semi-developed materials). By manipulating the ingredients of the materials to find meaningful combinations (for example, the combination of certain ingredients makes the surface of the material evoke specific emotions of the observer).

Creating materials experience vision

This step guides designers to explore the functions and experience that the material may create in the product, and even broader discussion space, such as society and the planet. This is also the ultimate goal of the design process, an definition of the final material vision.

Manifesting materials experience patterns

According to the material vision defined in the previous step (that is, the role played by the target material and the meaning it brings), this step will help the designer to transform the meaning of the created material vision into the formal quality of the new product (that is, how to formalize the material vision to reflect the intended meaning). This step is based on the MOM model (see Figure 37) and identifies the components that play a key role in giving the intended meaning.

Creating material/product concepts

The designer integrates all the findings from the above steps into the design stage and proposes a material or product concept.

Waste coffee ground material as an example - Step 2 outcome

Material experience vision (design intention)

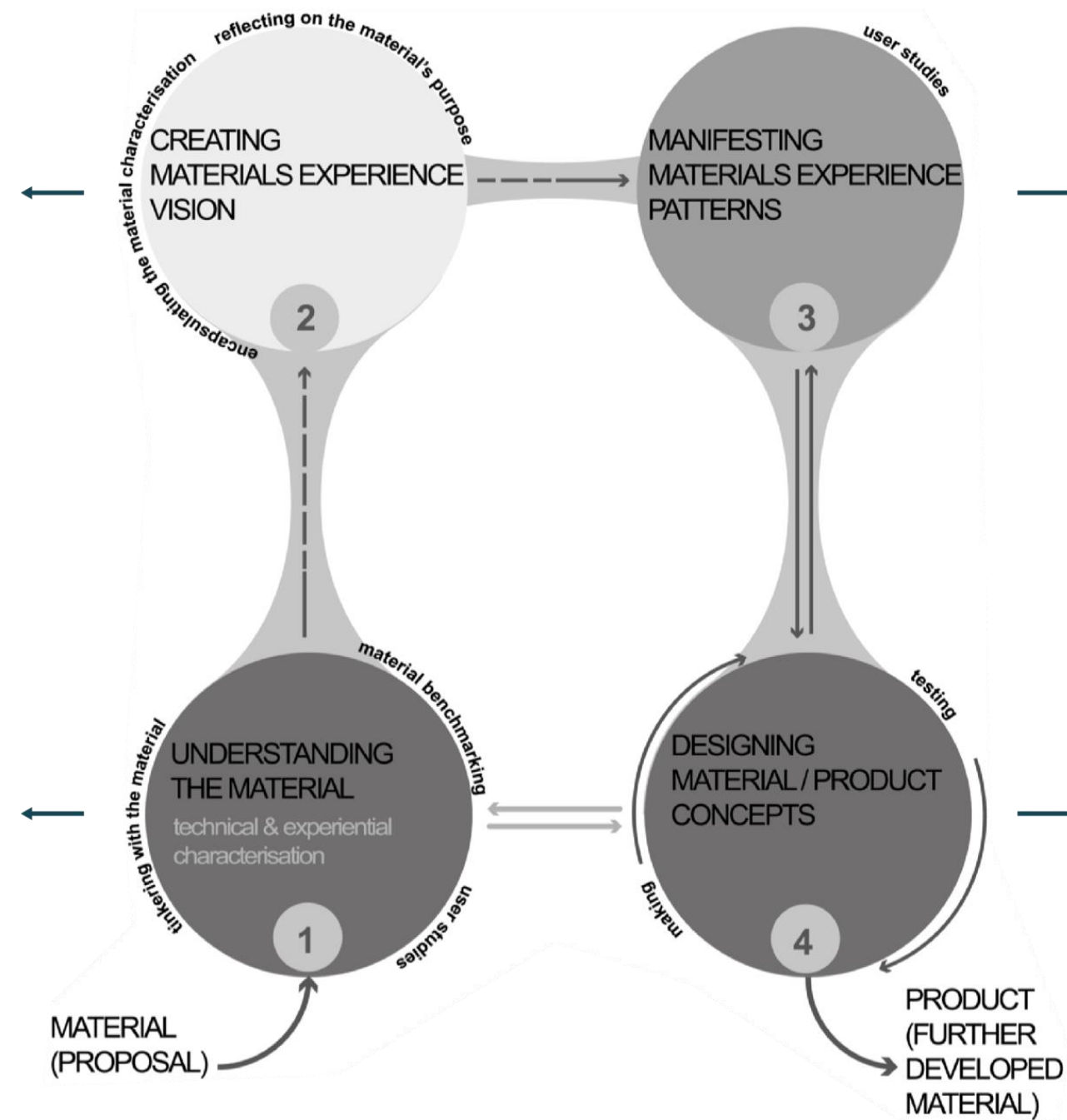
Given the unique quality of the material (potential fertilizer use), people no longer treat it as waste. And its imperfect surface quality can create materials with individual characteristics and bring a unique sensorial experience. (Design for environmental sustainability)

Waste coffee ground material as an example - Step 1 outcome

Technical characterization (eg. particles in ground will decrease the strength of material, can be made in bulk, can be used as nutrient for plant and good fire-resistance...)

Experiential characterization (eg. unique scent and colors are two important sensorial properties, the pre-settled meanings of material detected are eco-friendly and natural...)

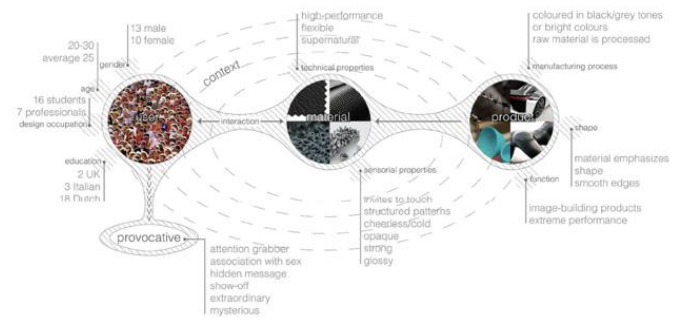
Material benchmarking



Waste coffee ground material as an example - Step 3 outcome

Manifesting materials experience patterns (visualization)

Based Step 2 vision insight, visualisation of 'modest' (Figure 3.6) and 'provocative' (below) data sets as 'materials experience patterns' based on The Meanings of Materials Model



Waste coffee ground material as an example - Step 4 outcome

Final material/product concepts

Final product concept 'Cof2Grow' (right) consisting of a tablet made of Café Maché, which contains seeds of preferred greens (left above); a pot made of CapPurcino, which will change over time slowly due to the influence of UV and touch (left below).

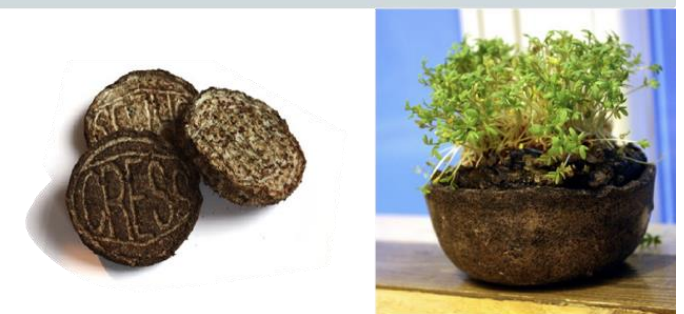


Figure 39 MDD method framework and application case (Karana et al., 2015)

Selection factors and content

MDD proposes a material exploration activity to inspire specific materials/product experience design, focusing on materials that are not fully developed. The information about material properties obtained through tinkering is the basis for the application of relatively unknown materials. Simultaneously, designers need to conduct material study and user research to acquire know-how of the new materials potential in design.

Four different levels of the material in terms of experience aspects have been determined: sensorial, interpretative (meanings), affective (emotions) and performative levels (Giaccardi & Karana, 2015). Creating a unique experience by adjusting the four elements of experiential levels, so that products made based on specific materials get the desired product experience.

Interactive way of selection

Participants: designer, material scientist, user

Interactive form: This method emphasizes that designers conduct a large number of material experiments in the face of unknown materials to explore different material samples. In addition, the interaction between users and designers is an extremely important part. In the stage of understanding the material, identifying the experiential levels of the material requires a large amount of user evaluation information. They help designers understand such things like sensorial characteristic of the material, people's views on the meaning of the material, the emotions it causes, and the interaction with the material.

3.1.6 Summary

Through the above study, it can be determined that different from the technical properties of materials that engineers pay attention to when selecting materials, designers usually pay attention to the abstract aspects caused by materials, that is, experimental characterization of materials (Veelaert, 2020), such as sensorial property, user-interaction and material meaning aspects (Ashby & Johnson, 2013; Kesteren et al., 2008; Karana, 2009; Karana et al., 2015). These features have contributed to the formation of product aesthetics and user experience, which are important aspects for designers to shape a product. One of the characteristics of these material selection activities is that intangible qualities such as the certain product experience or the meaning that needs to be conveyed are the design requirements, and the material sensorial properties that affect the specific experience are explored and found by using focus groups, interviews and other user-involved design methods, then converted into corresponding physical properties of as the starting point for searching the material database. Correspondence tables have been designed for the relationship between aesthetic attributes, sensorial properties and physical properties, sensorial parameters attributing meanings to materials (Ashby & Johnson, 2013; Kesteren, 2008; Karana, 2010)

	Attributes	Modeling aesthetic attributes	Explanation
Sight	Transparency (Opaque, Translucent, Transparent, and Water-clear or Optical quality)	-	- Transparency is related to the crystal structure of the material, such as most ceramic are polycrystalline and the crystals scatter light, so they are opaque.
	Color	-	- It is related to the spectral reflectance curve of the object.
	Reflectivity (Dead matte, Eggshell, Semigloss, Gloss, Mirror)	-	- attribute that depends partly on material and partly on surface detail.
	Textured	-	-
Touch	Hardness/Abrasion Resistant	H	- H: Hardness; The surface of the material with high hardness is not easy to produce scratches, and it is easy to cause scratches on other items, and has good durability and is not easy to deform.
	Softness	$S=EH$	- S: Softness, E: Modulus, H: Hardness; If S is small, the material feels soft; as S increases it feels harder.
	Stiffness	E	- Stiffness, for a given shape, is directly related to the material property "modulus," E.
	Warmth/Coldness	$Q=\sqrt{\rho\lambda c_p}\sqrt{t}$	- Q: the heat per unit area leaving the finger in time t, the smaller the material, the warmer it feels; ρ : density, λ : thermal conductivity, c_p : specific heat
Hearing	Pitch	$P=\sqrt{E/\rho}$	- If p is small the material's pitch is low; as p increases the material's pitch becomes higher; P: sound frequency, E: modulus, ρ : density
	Brightness	$L=\frac{1}{\eta}$	- If l is small the material sounds muffled; as l increases the material rings more; η : loss coefficient, L: sound brightness
Taste/Smell	Bitter	-	-
	Sweet	-	-

Figure 40 Relationship between aesthetic attributes and physical attributes (Ashby & Johnson, 2013)

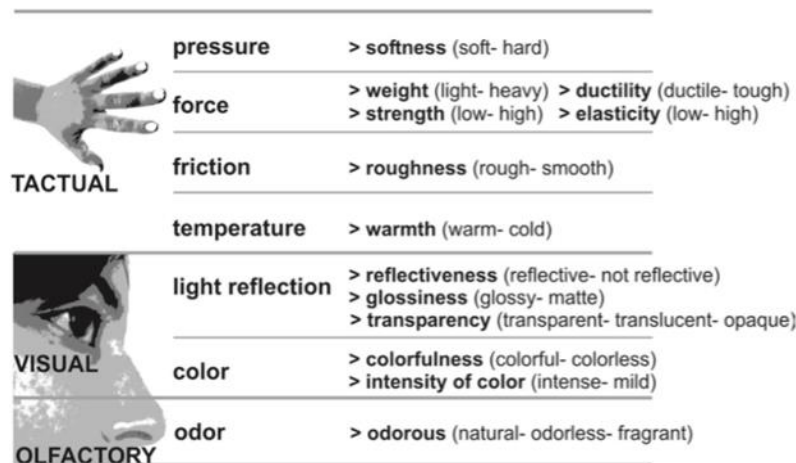


Figure 41 Sensorial parameters attributing meanings to materials (Karana, 2010)

The Products, Materials and Processes database is a material selection information database for facing product designers based on the CES database. Database presents the material feature of design through case studies. The material properties are visualized in the form of a map, which is convenient for comparing the difference in characteristics between materials to make the optimal choice. MiPS organizes designers and clients to discuss the product images and samples to form a common understanding of the expected perceptual aspects, and further internal discussions between designers determine the sensorial properties that dominate user-product interaction experience. The online tool developed by Karana helps designers understand the meaning of materials. Designers can navigate through the collages and get inspiration for using specific materials to reflect specific meanings. MDD method provides guidance for designers to explore and apply unknown materials. The purpose is to help designers understand and use new materials to shape product use and experience. Among them, tinkering is an important means to identify the potential uses of new materials.

SELECTION METHOD	Material selection for product design (Ashby & Johnson, 2013)	Material in product design(MiPS) (Kesteren, 2007)	Meaning driven material selection (Karana, 2010)	Material driven design (MDD) (Karana et al., 2015)
MATERIAL SELECTION FACTOR	<p>4 dimension of materials considered: engineering/usability/environmental/aesthetics and personality (Ashby & Johnson 2013, p.63-95)</p> <ul style="list-style-type: none"> © Technical attribute © Processability © Aesthetic attribute © Eco attribute © Perceived content of material in product 	<p>User-interaction aspects of materials(<i>material affects the use and experience aspects of a product</i>), other material requirements related to product specification (Kesteren, 2007)</p> <ul style="list-style-type: none"> © Sensorial property © Physical property 	<p>The material to evoke our specific feelings is a comprehensive function among users, products and materials. Critical aspects that give meaning to materials considered: user, material, product (Karana, 2010)</p> <ul style="list-style-type: none"> © User aspect (ethnography) © Material aspect (sensorial and physical property) © Product aspect (shape,function,manufacturing process) 	<p>Material experience is composed of four levels of material experiential quality components (Giaccardi and Karana, 2015)</p> <ul style="list-style-type: none"> © sensorial (aesthetic) © interpretative (meanings) © affective (emotions) © performative (behaviors)
MATERIAL SELECTION RESOURCE (DATABASE/METHOD)	<p>Database:</p> <ul style="list-style-type: none"> © Products, Materials and Processes database (Granta 2016) <p>Methods and tools:</p> <ul style="list-style-type: none"> © Selection based analysis / synthesis / similarity/inspiration © Identifying a structure for solving material selection problem: identification - material selection - implication 	<p>Database:</p> <ul style="list-style-type: none"> © Existing material database <p>Methods and tools:</p> <ul style="list-style-type: none"> © MiPS method: definition - translation - searching © Tools: picture, sample, question tool © sensorial-physical properties relation sheet 	<p>Database:</p> <ul style="list-style-type: none"> © Interactive material database (also an interactive tool that enables designers to browse specific materials and the conditions that evoke specific meanings) <p>Methods and tools:</p> <ul style="list-style-type: none"> © Meaning Driven Materials Selection based on meaning of material selection model © Sensorial property scales 	<p>Database:</p> <ul style="list-style-type: none"> – <p>Methods and tools:</p> <ul style="list-style-type: none"> © Material Driven Design (MDD): A method for guiding the construction of material experiential qualities to form desired product experience, focusing on underdeveloped materials <p>Process (first 3 steps order is not fixed):</p> <ul style="list-style-type: none"> <i>understanding the material</i> <i>creating materials experience vision</i> <i>manifesting materials experience patterns</i> <i>creating material/product concepts</i>
INTERACTIVE WAY	<p>Database presents the material feature of design through case studies. The material properties are visualized in the form of a map, which is convenient for comparing the difference in characteristics between materials to make the optimal choice.</p> <p>The database includes both material engineering and design aspects, promoting internal communication between designers and engineers.</p>	<p>Designers and clients discuss the product images and samples to form a common understanding of the expected perceptual aspects.</p> <p>Internal discussions between designers determine the sensorial properties that dominate user-product interaction experience.</p> <p>Communicating with materials scientists to obtain professional advice.</p>	<p>Navigating through the collage, to stimulate the designer's idea of giving meaning to materials.</p> <p>Identifying expected meaning arousal pattern of the materials from user study data, high interactivity between user and designer.</p>	<p>From the perspective of product use and experience, it provides designers with guidance when exploring and applying unfamiliar materials: tinkering, material benchmarking, materials experience vision, etc.</p>

Figure 42 Product material selection study in academic context

3.2 Material Selection Study in CMF Discipline

3.2.1 Study background: Material consideration in CMF design

CMF is the abbreviation of color, material, and finishing. As an independent professional field in the product development process, CMF discipline has gradually been valued in recent years (Becerra, 2016; Isoaho, 2016; Li et al., 2019). It focuses on giving products aesthetic quality and function through innovations in product colors, materials, shaping and finishing processes and patterns, establishing a specific emotional connection with users, and stimulating their desire to buy (Becerra, 2016; Li et al., 2019). CMF design tends to comprehensively enhance product competitiveness from the perspective of product visual quality without major adjustments to product architecture and functions (Li et al., 2019) (Figure 43). In commercial practice, CMF design has become an independent design position, assisting the ID design team in designing and assigning product materials, colors, and finishing. Therefore, studying the characteristics of material selection activities in CMF design can help us identify the designer's consideration on materials in business practice.



Figure 43 Oppo R11 - FC Barcelona Limited Edition, CMF design innovation

The main content of CMF design is to establish an emotional identity of mutual respect between humans and objects in the color, material, finishing, pattern, and human sensory system (Li et al., 2019, p.13). Li believes that the four elements of product CMF aspect (CMFP: Color, Material, Finishing, and Patterns) have a hierarchical relationship with the interaction of human sense and emotion, and proposed the CMFPSE theoretical model (Figure 44), the relevant elements involved in the CMF design are summarized into three levels based on the basic characteristics of the knowledge structure. Among them, materials and related

processes, as the material form, determine the form of coverage and interaction and are the basis for creating the final emotional experience (Li et al ., 2019, p.14).

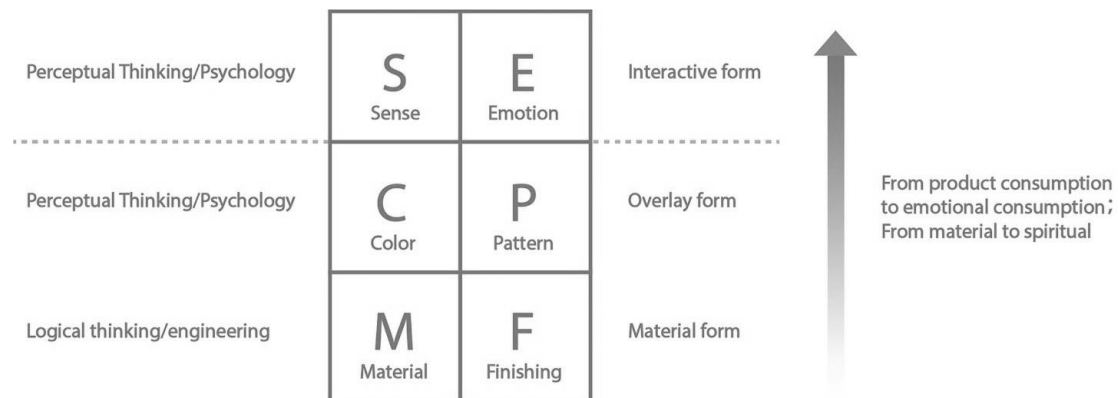


Figure 44 Schematic diagram of CMFPSE theoretical model (Li, 2019)

Material and process selection as an important activity of CMF design has a special perspective of thinking. CMF design practitioners mainly focus on the visual and somatosensory effects that can be achieved by materials and processes, the matching degree with the product, and the emotional identity with consumers (Li et al., 2019, p.78). Product processing technology, color and many other factors that determine consumer experience will be affected by the choice of materials. For example, different material properties and surface quality will interact with light in different ways (eg. reflection, absorption, etc.), thereby defining the surface color and roughness of the final product (eg. iridescent object, Figure 45). Materials that need to achieve a specific visual quality require different processing techniques (eg. aluminum surface texture under milling process, Figure 45b). In addition, due to material characteristics and finishing technology, some materials can only exhibit specific color effects. Therefore, for CMF discipline, the important information related to materials not only focuses on the technical properties, but more importantly, it describes the potential of the material under different processing techniques, color application possibilities, and assists CMF designers to better express the perceptual appearance of the material the product.

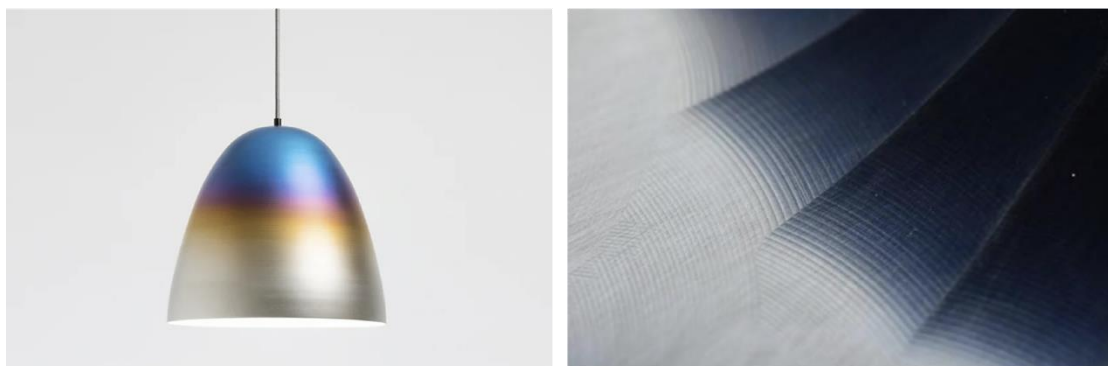


Figure 45 'the burning metal project' by hamanishi DESIGN (Left), milling of the Suzuri Series of table and bench seats by Alex Rasmussen, Neal Feay (Right)

3.2.2 Study content and purpose

This part of the study focuses on the material information considered by CMF designers in CMF design practice and related aspects that affect material selection. Due to the relatively limited resources in the CMF field, two CMF professional books (Becerra, 2016; Li et al., 2019), a review paper on CMF (Isoaho, 2016) and a lecture shared by Reiko Morrison (the founder of Blinkid) are selected as the main research data (Morrison, 2016). The study content is as follows:

- ***Investigating the CMF design process and main activity characteristics.***
- ***Determining the designer's consideration of materials in the CMF design process, and identifying the critical material information considered by the CMF designer.***
- ***Typology of CMF elements related to the material, and determining the material properties considered by the CMF designer in the material selection process.***

The purpose of the above study content is to clarify the way CMF designers use materials and the material information they pay attention to in the process of executing certain projects. These insights can be used as the design support of the recycled materials database to bring designers more usability for material selection in commercial perspective.

3.2.3 CMF design process and main activities

The following Figure 46 summarizes the study of CMF design process from four aspects: the main activities under different stages, the design methods and tools involved, and the relationship with the ID process (Becerra 2016; Morrison 2016; Isoah 2016; Li 2019). Through this study, the tasks that CMF designers need to complete in different design stages and the characteristics of activities in different stages can be identified.

The CMF design process and the ID process run in parallel (Becerra, 2016). Three main stages can be determined: market and trend insight, CMF design, and production landing. Market and trend insights correspond to market and user insights in the ID process, requiring CMF designers to complete pre-research related to the project (Figure 46-market & trend insight). At this stage, the designer will determine the CMF practice direction according to the requirements of the product brief (for example, upgrading color of previous product), and analyze the large amount of external information obtained into the elements of the product CMF aspects in a visual and situational way. Presenting a trend proposal that conforms the needs of the project. The external information analysis includes not only the CMF research and user insights on the target product, but also the influence of the trend information in different dimensions on the CMF design elements.

The CMF design stage mainly matches the CMF elements onto product architecture. Designers consider the relationship between CMF assignment of different components and overall product effects (for example, whether the parts finishing can meet the expected function or

how to break up parts based on certain CMF solution, etc.) (Figure 46-CMF design).

During the product landing stage, CMF designers would communicate with the resident engineers, continuing to test based on material, process and samples, to ensure that the effects of the CMF solution are met (Figure 46-product landing).

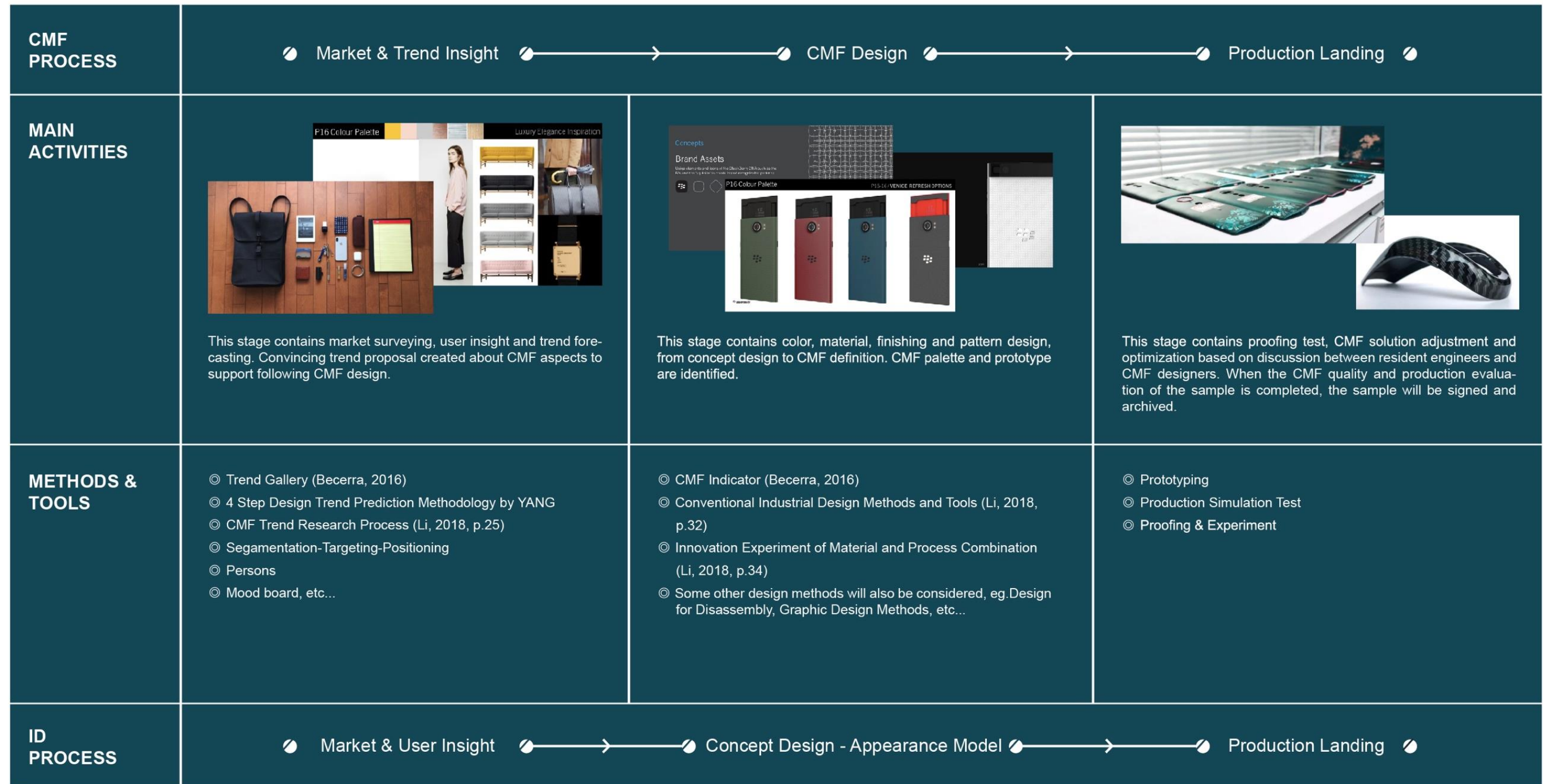


Figure 46 Study result of CMF process and main activities

3.2.4 Material considerations in the CMF design process

Figure 47 summarizes the material-related information, the material aspects considered by designers and the material selection factors in different CMF design activities. This information is obtained through the analysis of CMF design cases and related professional tutorials (CMF design cases from published projects of ID-BLINK by Morrison; professional tutorials based on Becerra, 2016 and Li, 2019)




CMF PROCESS	● Market & Trend Insight —————> CMF Design —————> Production Landing ●		
MATERIAL RELATED INFO.	<ul style="list-style-type: none"> ◎ Pre-requirements about material (eg.assigned material type...) ◎ Possibility of colors, surface finishings, shaping processes and pattern effects of different materials ◎ Material feedback from consumer, contains functional and emotive attribute ◎ Information on the pros and cons of material in competitive product 	<ul style="list-style-type: none"> ◎ The story and evocative content carried by the material in a specific context ◎ Material combination proposal based on functional and emotional requirements of products ◎ Material processing characteristics and the achievability of related surface effects applied ◎ Experience and evaluation with material sample 	<ul style="list-style-type: none"> ◎ Material specification ◎ Experience and evaluation with parts sample 
MATERIAL ASPECTS CONSIDERED BY DESIGNERS	<ul style="list-style-type: none"> ◎ Material Type and Application Field ◎ Material Appearance and Trend ◎ Material Reputation and Documentation ◎ Material Function and Limitations 	<ul style="list-style-type: none"> ◎ Evocative contents and story that materials can bring ◎ Material matching effects in actual products ◎ Material manufacturing process, finishing process information ◎ Material physical sample 	<ul style="list-style-type: none"> ◎ Whether the product / material meets the engineering test ◎ Whether the material appearance meets the expectations of the CMF designer ◎ Whether the product / material meets the manufacturing test
MATERIAL SELECTION FACTOR	<ul style="list-style-type: none"> ◎ Technical property ◎ Sensorial property (mainly visual aspects) ◎ Material interpretative, affective properties ◎ Eco property ◎ Economic and supply factor 	<ul style="list-style-type: none"> ◎ Technical property ◎ Sensorial property (mainly visual aspects) ◎ Material manufacturability ◎ Economic and supply factor 	<ul style="list-style-type: none"> ◎ Technical property ◎ Sensorial property (mainly visual aspects) ◎ Material manufacturability ◎ Economic and supply factor

Figure 47 Material selection study in the CMF design process

Critical material information considered by CMF designers can be determined:

Material attributes in CMF design

Three types of the material attributes are identified by Becerra: functional attributes, emotional attributes and neutral attributes, as shown in the Figure 48 (Becerra, 2016, p49-CMF indicator). While, Li determined the basic characteristics of CMF materials: physical characteristics, chemical characteristics and extension characteristics. Further, for the extension characteristics, four sub-characteristics are identified: processability, perception, surroundings and economic characteristics, as shown in the Figure 49 (Li, 2019, p79-81). According to the above study, the material attributes that are critical to CMF design can be divided into two aspects, the inner characteristics of the material and the external characteristics of the material. The former can be understood as the physical, chemical, and sensorial characteristics of the material itself, while the latter is affected by a series of external factors, such as the emotional characteristics of the material, processability, and economic characteristics. For CMF design, physical characteristics related to product functions, sensorial characteristics that shape product personality, processability characteristics, and economic characteristics are the focus of attention for designer. CMF designers pay more attention to the process that can be implemented on the surface of the material and the final effect it presents (coloring and finishing process), instead of the material itself.



Figure 48 C/M/F indicator and material attributes in CMF design (Becerra, 2016)

Basic characteristics of CMF materials by Li	
Material Characteristic	Explanation
Physical Characteristic	Physical characteristics are an important basis for controlling various physical phenomena and product quality innovation, such as density, thermal conductivity, insulation, etc. Automobile color film is a typical design that makes reasonable use of the physical properties of materials.
Chemical Characteristics	Chemical properties refer to the chemical properties of materials and their possible chemical changes under different conditions such as temperature, force, light, magnetic field and biological action. eg.light curing, compression heat generation.
Extension Characteristics	<p>Extension characteristics refer to the processability, perception, surroundings and economic characteristics of the material.</p> <ul style="list-style-type: none"> - Processability characteristic: Possibility of material in the forming process - Perception characteristic: The comprehensive impression of the material produced by the human sensory system - Surroundings characteristic: CMF material is suitable for application environmental conditions, such as water resistance, high temperature resistance, etc. - Economic characteristic: Economic indicators of materials in practical applications, such as material prices, processing costs, and recycling costs

Figure 49 Basic characteristics of CMF material (Li, 2009)

Material trends and stories

Material trends reflect the qualities of materials that consumers/markets may expect in a certain period of time in the future. It is influenced by a series of external factors such as social culture, consumer preferences, etc. According to the trend hierarchy (OMUUS, 2013), the material trend can be explained in 4 dimensions, namely:

a.Megatrend (for each trend level relevant examples are listed below)

In the face of global warming, we put forward the slogan to embrace earth, and nature trends encourage us to use more earth-friendly materials and nature finishes (Trendbook, 2021).

b.Social-Culture trend

Materials gender-neutral style color and finishing can be seen as the result of freer values and equality between men and women.

c.Consumer&Behavioral trend

Material with rustic/aged looks can be appreciated by some western europeans, considered a symbol of spiritual and moral enlightenment.

d.Product&Seivice trend

Packaging made with biodegradable materials, eg.bioplastic film.

Various material trends need to be visualized in the material appearance qualities and other functional elements (CMF design elements) for designers usage. Figure 50 is a case study conducted by author that examines how material trend information is determined by design trends. This research shows that the trend information of materials can be combined with the sensorial characteristics of materials to give designers inspiration in the use of materials.

Trend insight goals: forecast 2021-2022 Chinese design style, Material/Color/Finishing/Pattern trend

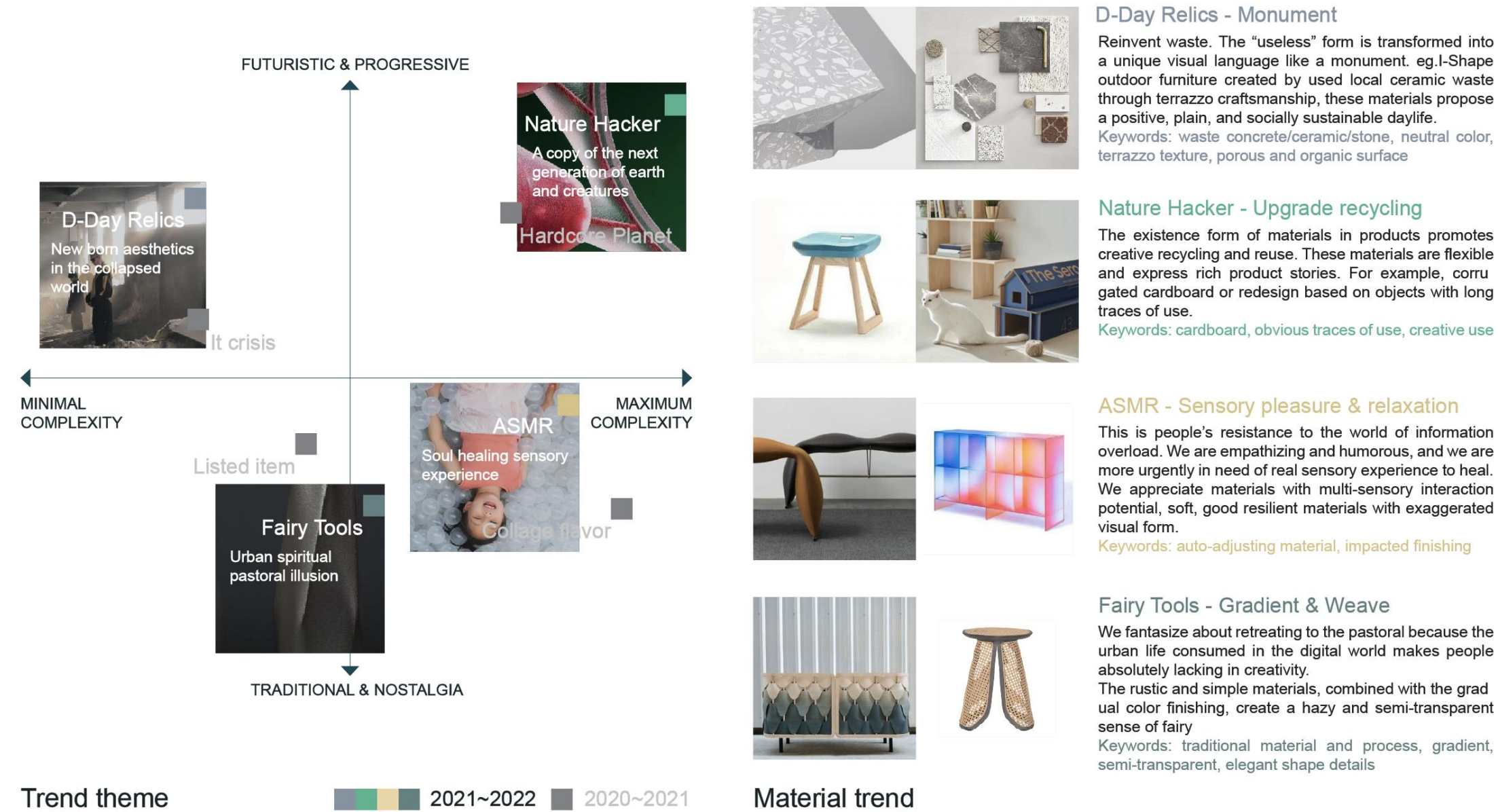


Figure 50 Fig 3.17 The cross image on the left is trend forecasting of Chinese design styles in 2021-2022 by Yang Design, and on the right are the material trends under different design trends organized by author, it clear shows that material appearance quality contributes style and trend of product design.

Creating narratives and constructing stories are important means of establishing emotional links between products and consumers (Becerra, 2016). This work includes visualizing CMF design elements and connecting them with consumer appeals, emerging consumer behaviors, and other hot events that occur in the real world. The content of story presented needs to impress consumers and promotes consumer's recognition of the final product/brand. Material story information can play an important role here. On the one hand, designers can create certain stories based on material performance for products to attract consumers, such as Nike Flyknit, illustrates the fact that the shoes are created with an ultra-strong yarn knit woven into different textures, shaping the form and eliminating unnecessary weight. On the other hand, they can start from the story of the material itself, for example, some materials have certain natural and regional cultural characteristics. The use of such materials can convey different spirits or attitudes of products/brands. For example, the black wood produced in Poland symbolizes inheritance and profound aesthetic quality in the eyes of Chinese consumers. Designers could win consumers' praise by considering the story behind the material and assigning it to the product manufacturing.

Material and inspiration

CMF designers usually learn from cross-industry CMF elements, such as applying colors and textures that are currently popular in the clothing industry on the surface of certain products. In addition, they will also learn about the manufacturing and finishing processes used in different industries, and introduce new materials to improve product performance or optimize, integrate processes to improve production efficiency and reduce cost.






3.2.5 Typology of CMF elements related to materials

Materials have intrinsic qualities and imposed qualities, these qualities are determined by material itself or specific operations on materials (Li, 2019; Rognoli, 2010), and designers are more obsessed with imposed qualities. Figure 51 is the material information chart defined by author for CMF designers usage based on facts that have been found, here taking material — douglas fir as an example, a high-performance wood native to northwestern United States, widely used in furniture, interior industry. The critical material characteristics considered in this chart are divided into sensorial properties (mainly focusing on visual aspects) and physical properties. According to the material as the product body or the covering material, it is divided into formed material (eg. shell material) and decoration material (eg. coating materials). In addition, for color characteristics of material, it uses the HSB format, because it can be better matched with the Practical Color Coordinate System¹¹ (the system presents colors in a way suitable for designers to use). The value represents the color characteristics of the material image rather than the material itself due to measurement limitations.

¹¹ Practical Color Coordinate System (PCCS) is a discrete color space indexed by hue and tone. It was developed by the Japan Color Research Institute in 1954 (Wikipedia, 2021).

WOOD

Formed Material

Douglas Fir (Pinus)		Finishing process							
Material property		<ul style="list-style-type: none">● Color: light rose● Transparency: opaque● Reflection: matte● Pattern: 2D, fine to medium <ul style="list-style-type: none">● Mechanical, thermal properties: good strength to density ratio, good thermal insulation● Electromagnetic properties: good electrical insulation	<p>Process: Laser engraving</p> <p>Design consideration: better carving effect for wood with high oil content; waxing/ lacquering...before lasering; laser speed and tem. should be calibrated for composite wood veneers; finer,tight grain surface will yield more constrasting design.</p>						
		<p>Color: light rose</p> <p>Color explanation: From the heart to the sapwood, it changes from light red to light yellow. Early wood and late wood are distinct in color, with the latter having a darker, sharper band.</p> <p>Color value(HSB):</p> <table><tr><td>21,13,96</td><td>90,3,11</td><td>230,189,143</td></tr><tr><td>66,13,18</td><td></td><td></td></tr></table>	21,13,96	90,3,11	230,189,143	66,13,18			<p>Process: PU coatings</p> <p>Design consideration: divided into water-based and oil-based polyurethane, the latter is more toxic; a strong isolation layer is formed on the surface, which retains the texture beauty and soft touch; prone to breakage and UV damage</p>
	21,13,96	90,3,11	230,189,143						
66,13,18									
	<p>Pattern: 2D, fine to medium</p> <p>Pattern explanation: The wood grain are straight, the older the tree, the sharper the visual contrast of the grains, especially in vertical cutting.</p>	<p>Process: Lacquering</p> <p>Design consideration: drying time is slower than PU coatings, multi-layer brush coating; less durable, but more flexible and better resistant to UV damage; usually cheaper than polyurethane and low toxicity</p>							
Intrinsic color			<ul style="list-style-type: none">○ Imposed color: dark brown○ Imposed pattern: new complex, high contrast pattern						
			<ul style="list-style-type: none">○ Imposed color: deepen previous color○ Imposed reflection: gloss○ Imposed pattern: more constrasting pattern						
			<ul style="list-style-type: none">○ Imposed color: deepen previous color○ Imposed reflection: gloss○ Imposed pattern: more constrasting pattern						

Decoration Material


Douglas Fir Veneer		Finishing process	
Material property		<ul style="list-style-type: none">● Color: light rose● Transparency: opaque● Reflection: matte● Pattern: 2D, fine to medium	<p>Process: Dyeing</p> <p>Design consideration: divided into pigment and dye-based pigment, The latter can penetrate deeper into the wood, but is more sensitive to ultraviolet rays; Dye dyeing used in more refined applications, giving surface a even, darker and clear color</p>
		<ul style="list-style-type: none">● Mechanical, thermal properties: better physical stability, moisture resistance, good breathability● Electromagnetic properties: good electrical insulation	<p>Imposed color: a variety of colors depend on the colorant</p>

Figure 51 CMF material information chart — taking material - douglas fir as an example

3.2.6 Summary

This section identifies the material-related information considered by the designer in the CMF design: material inner and the external characteristics, material trends and stories, information that inspires material usage. The characteristics of activities in different stages of the CMF design process are investigated. The material information chart for CMF designers usage is designed by typology of CMF design elements related to materials. This table reflects the material inherent properties and imposed properties, of which imposed properties and processes that enable change material properties are linked to allow designers to determine the changes that different processes impose on materials.

Chapter 4 Recycled material database design

4.1 The reason for building a recycled material database

As mentioned in Chapter 3, the material database organizes material-related information in a quick retrieval way and meets the search needs of designers, so that they can compare and choose suitable materials for the dedicated project when faced with a large number of diverse materials. According to the investigation of material database in Chapter 3, it has been determined that there are different types of material databases to support material selection in design appeals: CES Products, Materials and Processes(Granta 2016), interactive database based on the material meanings(Karana, 2009) and some well-know inspired material library reviewed by Veelaert: Design insite, Materio, Material Connexion, etc. Although these databases contain a large number of innovative materials and support different goals of material selection activities, they lack information focused on the organization of recycled materials. Given the unique advantages and potential of recycled materials that are identified in Chapter 2, it is necessary to form an knowledge presentation system suitable for recycled materials for designers to check. In addition, existing well-known databases related to recycled material resources, such as Rematerialise (Dehn, 2014), usually only used as a place to store information about recycled materials. Although such databases present information about recycled materials, it lacks interactivity with the material selection activities by the designer for the project at hand, so it is difficult for designers to actively notice and use such database when facing actual projects. Therefore, the recycled materials database to be constructed in this chapter will consider material selection activities in commercial practice (material considerations in CMF design), forming a database that focuses on presenting information about recycled materials in product design aspect, loaded with a built-in design tool to assist designers find design opportunities with recycled materials based on the project at hand.

4.2 Idea of Database

In this chapter, a recycled material database is developed based on the insights gained in chapters 2 and 3, encouraging designers to introduce recycled materials into projects.

Presentation of experimental material information

According to the data analyzed in Chapter 2, recycled materials include both commercial materials (64% of the collected cases) and a significant number of experimental materials (36%). In the former case, reliable information on material parameters, application fields and supply capabilities can usually be obtained from developers or suppliers. The latter are experimental materials that are explored by material developers and designers in research institutes, workshops and universities. Typically, these materials exist in prototype, semi-developmental stages, and are not available for mass production, making them less likely to be of interest to product designers from a practical application point of view. However, these materials have a greater potential for plasticity and innovation than commercial materials, and as discussed in the MDD practice (Karana, et al., 2015), designers can experiment intensively

with the material components (e.g. Mixing, burning, machining, bonding, etc.) to shape fresh experiential aspects of the material. The idea here is therefore to present public information on the ingredients (eg. Waste origins, bonding material, etc.) used in these experimental materials, the making process and other information that can aid material exploration, facilitating product designers/material developers to identify more design opportunities and experiment with recycled material.

Database structure and interaction design

We can identify similarities and differences between the material selection approach under the academic context for product design and the CMF design approach in commercial practice. The former emphasises the exploration of the needs of a particular product-user experience as a precondition for finding the physical factors that influence a specific experience through focus groups, interviews and other user-involved design methods; additionally, it defines the desired sensorial and technical properties of the material to be used as a starting point for retrieving the material candidate from the database (Kesteren et al., 2007; Karana, 2010). The latter, instead, focuses on defining the material appearance qualities in relation to users, markets, aesthetic trends, etc., in order to obtain material solutions with the persuasion effect of perceptual consumption. Material as one of the basic elements of CMF design is not so easy to change compared to color, finishing process and surface pattern, and designers are more interested in examining what can be applied to the material, and ultimately what changes can be made in the material's visual and somatosensory effects (Becerra, 2016; Morrison, 2016; Isoah 2016; Li et al., 2019). Therefore, for the design of a materials database with high utility, consideration should be given to the material considerations of the designer in the CMF design process and the way in which material information is accessed. Additionally, material selection under the academic perspective develops material properties in more depth, considering more dimensions of the sensorial property of the material, which can inspire product/CMF designers to design in areas where they do not specialise in experiential elements, such as touch, taste aspects or even the associations that the material surface evokes (van Kesteren et al., 2007; Karana, 2010; Li et al. , 2019).

The design of the recycled materials database should therefore firstly support the information that CMF designers pay attention to when retrieving materials (e.g. CMF elements related to material, material trends, typical application for specific finishing process, etc.) and support direct visual access to material information, making it more direct and higher utility. Another key factor is to present the unique potential of recycled materials, as we need to admit that the advantages of traditional materials are significant, and if we hope designers to make transformative choices of recycled materials we need to make them aware of the pros of recycled materials, such as their potential for product architecture innovation, superior manufacturing methods to traditional materials, etc, as mentioned in Chapter 2.

Furthermore, as material selection activities are integrated into the product development process (for commercial design, material selection activities are usually integrated into the CMF design process parallel to the product development process), the material information in the database should be presented in different ways, interaction forms and support the

visualization of recycled materials to support designers' exploration of materials at different design stages. The aim is to better inspire designers to get inspiration from recycled materials, support the consideration of materials in the design reasoning process at different stages.

4.3 Basic framework and content introduction of the database

As shown in Figure 4.1 the recycled materials database consists of four parts:

- Recycled material knowledge base;
- Materials exploration module;
- Downloading center; and
- Sharing platform.

The material knowledge base is a storage unit for recycled material information and consists of six data boards: Material-Attribute Board, Material-Process Board, Material-Experiment Board, Material-Product Board, Material-Pros Board and Material-Trends Board (Figure 52). The Material-Attribute, Material-Process, Material-Product information is based on the schematic of an information structure for product design proposed by Ashby, so the information organization is similar to CES Products, Materials and Processes (Granta 2016), but the correlation between material attribute and processing process is strengthened. As discussed in Chapter 3, designers are more concerned about the multiple possibilities formed by applying different processes to materials, so the changed attribute information will be displayed on the Process-Board to inform the designer of the physical and sensorial properties of the material that can be changed through the manufacturing or finishing process. The Material-Experiment board contains relevant information to support the material development: ingredients, ingredient introduction, making process. The Material-Pros board describes the advantages and disadvantages of materials from the perspective of aesthetics, manufacturability, functionality and sustainability. The Material-Trend board considers information about recycled material trends in different hierarchy (For details, please see section 4.4.1).

Additionally, for the information retrieval and presentation form, the attribute-mapping form in CES is used for reference. Designers can directly change the material properties to be viewed and perform material visually screening to provide an intuitive comparison of characteristics between materials. In terms of presentation form, a color element-oriented material information display mode (clicking “color system button” in Figure 60, the display effect is presented in Figure 59 based on Parctical Color Coordinate is designed. The purpose is to facilitate designers better complete product design tasks, such as material color matching.

The Material exploration module is a built-in design and management tool for product designers or CMF designers. It consists of two parts: Material Inspiration Board and Visual Board Building Canvas. The module allows designers to import external images or drag and drop images from the material inspiration board to create visual boards on the canvas, such as recycled material mood boards and trend charts to aid product development. An important feature of this module is that it can recognize the visual elements of imported images (such as the color and outline shape in the images) to match the cases of recycled materials with similar

quality in database, and display them in the material inspiration board. Such a mechanism could provide the designer with suggestions or inspiration in terms of recycled materials based on the project at hand, in order to expand the current mood board and introduce recycled materials. In addition, this module supports designers to store external product/material images to support the generation of their own CMF material inspiration library. This information can also be loaded into the material inspiration board to provide designers with a CMF design inspiration library containing recycled materials to support design inspiration search, material selection and other design practice support.

The downloading center contains design materials such as various types of JPEG. texture maps and 3d pattern models in OBJ. format of recycled materials that can be compatible with mainstream 3d modeling software and rendering software, such as Rhinoceros¹² , 3ds Max¹³ or Keyshot¹⁴ , Cinema 4D¹⁵ , for quick simulation and test of the product design.

The following section will introduce in detail the various parts of the database and the different types of board design.

¹² <https://www.rhino3d.com/>

¹³ <https://www.autodesk.com/products/3ds-max/overview>

¹⁴ <https://www.keyshot.com/>

¹⁵ <https://www.maxon.net/en/cinema-4d>

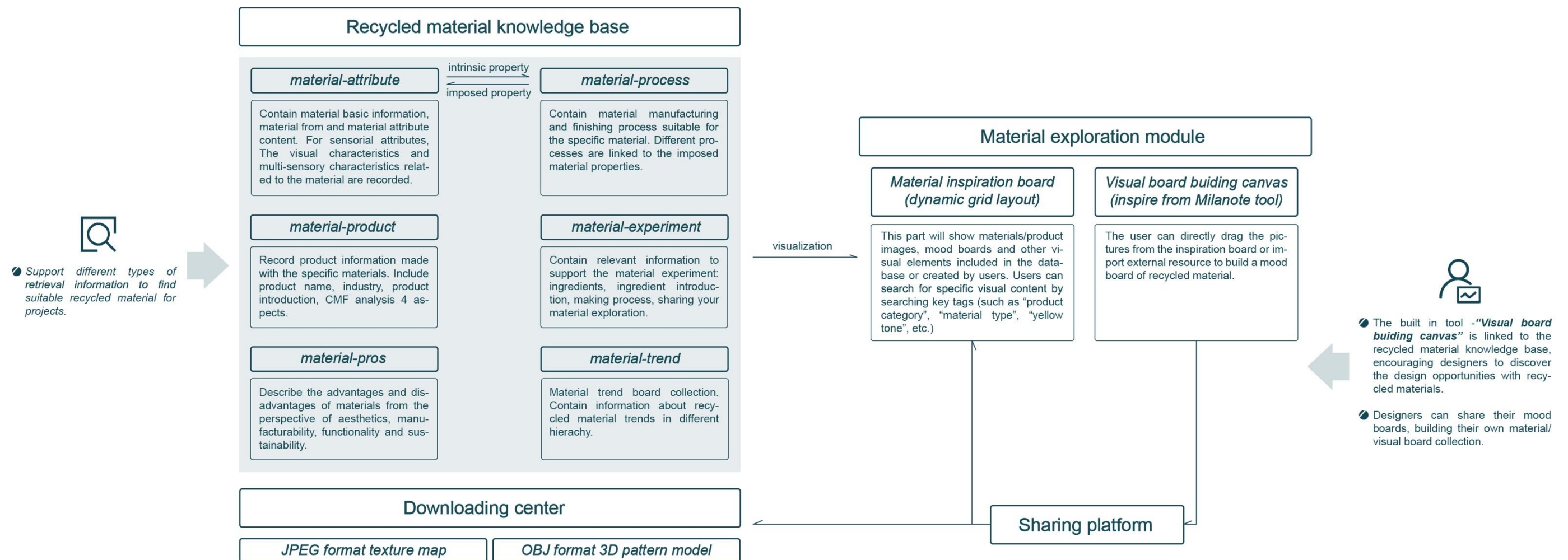


Figure 52 Framework of recycled materials database

4.4 Database Content

4.4.1 Part 1: Recycled material knowledge base

This part presents data of recycled material properties, material manufacturing and finishing processes, material application cases in product design, material potential, and material trend. The knowledge base has two important characteristics, the first is the link between the physical, sensorial properties of the material and the elements changed by the relevant processes. Considering the influence of different processes on different properties of materials is very important information for product/CMF designers (eg. the wood veneer has a deeper color effect through dye colorants compared with pigment colorant). The user can understand the imposed properties of the material through its acceptable process while understanding the inherent characteristics of the material. These two types of property will be presented to the user at the same time when the user retrieves one material. Secondly, recycled material trend information is presented through mood boards and timelines form, where users can correlate recycled material qualities with different dimensions of trend content to gain new insights into their practical applications. Below is a detailed description of the different boards, taking pectin-based composites (A06-SONNET155) as an example.

Material-Attribute Board, Material-Process Board

The Material-Attribute Board (Figure 53) consists of three parts: Basic information, Material form and the Material physical, sensorial attributes. The basic information presents the material name, type, feedstock & origin, developer, country, year, development status and market availability. The material form indicates the form in which the recycled material is available, e.g. Whether the material is supplied in sheet or film form, which is divided into six categories (particle/powder, cloth, film, sheet, bluk, 3d object) according to Chapter 2. Materials for similar purposes, which represent alternatives to certain materials, This is to associate recycled materials with existing common materials used in product design. For example, if some recycled materials have leather characteristics and are used in related products, they are classified as leather materials. Here 7 common materials are defined (metal, plastic, wood, glass, ceramic, soft material, coating). Material attributes have been developed according to the critical material parameters considered in the CMF design. They are divided into physical and sensorial properties, with sensory properties considering the material's contribution to the visual experience in CMF design (surface colour, transparency, reflectivity, surface pattern) and multi-sensory properties (material touch, sound, smell, taste feature) (Ashby 2013, Li 2019). Each property parameter is divided into two categories based on whether the material has inherent or imposed qualities. The imposed quality forms through the change of the inherent characteristics by the manufacturing process, and the intrinsic quality is the inherent characteristics of the material. Highlighting the quality of these two types of materials can enable the user to better understand the manipulability of the material, so this it will make the database more practical and flexible in practical applications.

Material-Attribute Board	
	Basic information Material name: Pectin-based composite (SONNET155) Feedstock & Origin: Mainly pectin, mixed with fibre. Pectin from by-products of the citrus food industry and fibers from cellulosic production waste of textile industry. PIW and PCW. Material type: organic material, natural composite Developer: Lobke Beckfeld, Johanna Hehemeyer-Cürten Country: Germany Year: 2020 Status: Experimental (material development phase) Market Availability: no
	Material form Material stock form: sheet, film Materials for similar purposes: leather, paper
	Physical attribute <input checked="" type="radio"/> Mechanical, thermal properties: <input checked="" type="radio"/> Electromagnetic properties: - <input checked="" type="radio"/> Durability:
	Sensorial attribute (visual / multi-sensory) <div>   </div> <div>   </div> <div>  </div> <div> Visual aspect <input checked="" type="radio"/> Color: variable Depending on natural pigment and fiber mixed. Pectin colors fall in the range between reddish purple (black currant and elderberry) and yellow (citrus), darker color with more fibers added. <input checked="" type="radio"/> Transparency: variable, from translucent to opaque Depending on cellulose percentage, length and density of the fibers. <input checked="" type="radio"/> Reflection: variable, from matte to glossy Depending on mould structure. <input checked="" type="radio"/> Pattern: 2D, fine to coarse Multi-sensorial aspect Tactility: skin-feeling like surface Acoustic: - Olfactory: - Taste: - </div>

Figure 53 Material-Attribute Board

The Material-Process Board (Figure 54) contains information on the appropriate shaping and finishing processes for one material, enabling the designer to read this content and gain direct access to the processability of the recycled material and the relevant process parameters that affect the property of the material. This includes five types of data: process name, process description, process diagram, design considerations and changed attribute. Through the analysis in Chapter 2, it can be found that the aesthetic quality and performance of recycled materials will be affected by the composition of waste materials and processing technology. The finding of the recycled materials application potential depends to a large extent on the designer-involved material development (such as case A03, A04, E08, etc.), through the inter-process combination experiment, changing the experimental conditions to obtain new materials. Therefore the process diagram and design considerations in the Material-Process Board provide information to support this exploration. At the same time each process is linked to the imposed property aspects of one material, visually presenting how the process changes the physical and sensorial properties of one material.

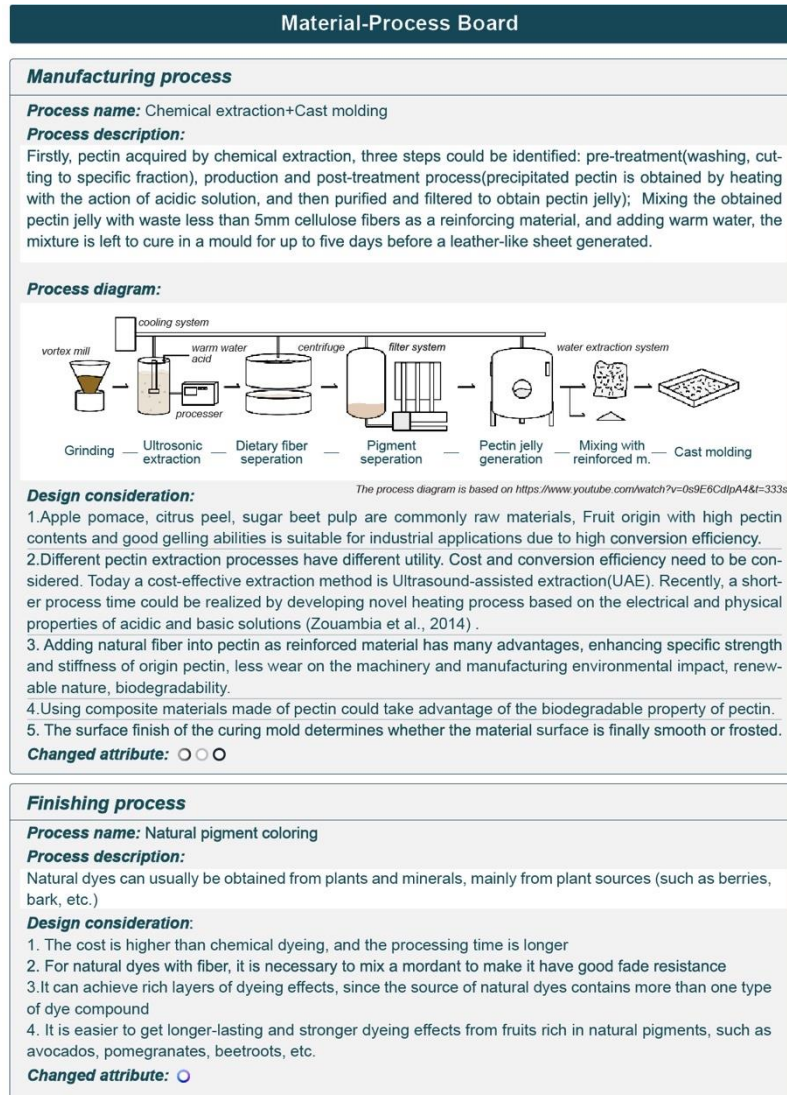


Figure 54 Material-Process Board

Material-Experiment Board


This section focuses on experimental material information, by presenting public information on the raw materials that make up the material, fabrication processes, material experimentation records and images that facilitate product designers/material developers to identify further design opportunities with recycled material (Figure 55). The content also supports material explorers to edit and share new insights. We hope that this content will support MDD practitioners.

Material-Experiment Board

Design with recycled material - Making pectin-based material

Materials: citrus peel, hydrochloric acid, distilled water, filter funnel, heating device, oven, dropper, ph test paper, heatable container, knife

Main ingredient introduction:



Citrus peel, rich in pectin (light yellow part of the orange peel), is also the first ingredient to be extracted in the experiment. Other fruits/vegetable plants rich in pectin include apple pomace, orange peel, and sugar beet pulp, also orange, lemon, and grapefruit peels which can be used as raw materials.

Making process:

I. Pectin jelly extraction from citrus peel

- cut the collected orange peels into small pieces.
- put the small pieces into a container with water, add the hydrochloric acid solution to the container little by little and stir constantly. Refer to the ph test paper to control the ph value of the solution in the container at about 2.8.
- heat the container to boiling
- after the solution in the container is cooled, pour it into a filter to obtain a viscous pectin jelly.

II. Mixing fiber, Cast molding to acquire pectin-based film

- mix short fibers into the viscous pectin jelly, add an appropriate amount of warm water and keep stirring, evenly pour it into the prepared flat plate, put it in the oven and heat it to solidify to form a pectin-based film.

Source: <https://www.youtube.com/watch?v=xRU8TeadHeM>

Sharing your material exploration:

Image upload area	Image upload area	Image upload area
description/finding	description/finding	description/finding

Figure 55 Material-Experiment Board

Material-Product Board

The Materials-Product Board (Figure 56) presents information on products made from the material, including the product name, category, country, developer, product introduction, and CMF design analysis, where the product description is derived from the designer's description of the project, obtained from the product exhibition website or studio website, and the CMF design analysis is based on images of the product/material presentation and reflects information on color, material, pattern and process.



Figure 56 Material-Product Board

Material-Pros Board

This section is a statement of the advantages of recycled materials (Figure 57), assessed in four perspectives: aesthetics, functionality, manufacturability and sustainability. This knowledge is based on relevant research article and publications.



Figure 57 Material-Pros Board

Materials-Trend Board

According to the material trend hierarchy discussed in Chapter 3, the trends could be divided into four levels, where the material trend are influenced by different hierarchies of information and thus work together to create the trend characteristics of the material about CMF design aspects (e.g. the popularity of a material may be influenced by technological innovation), designers usually find the trend content to be explored based on the project requirements (e.g. Understanding middle-aged women's aesthetic tendency towards mobile phones shell material). By collecting information on different trend dimensions, the designer will be able to integrate and expand the information on what materials, colors and finishes are popular and more acceptable to consumers. The idea here is therefore to design a trend board based on a trend forecasting approach around specific types of recycled materials (Li, 2019; Becerra 2016), where the content of the trend board is an illustration of how a phenomenal recycled material (e.g. Novel material made from food waste), is represented at different trend levels, ultimately ending up in a CMF design element for designers' reference. By combining and linking these trend board, designers can acquire new ideas about recycled material (Figure 58).

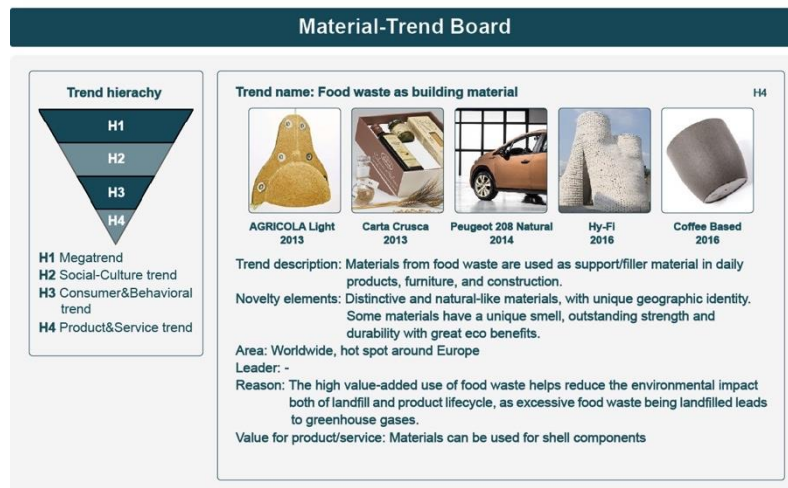


Figure 58 Material-Trend Board (material from food waste in product&service trend insight)

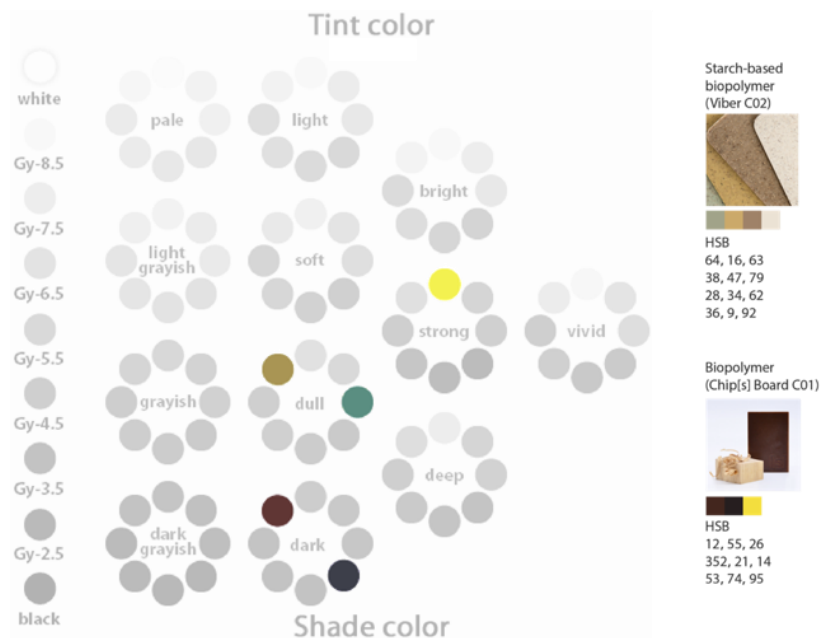


Figure 59 Color element-oriented material information display mode (This display mode could map the current material color information (HSB) to Parctical Color Coordinate. Designers can visually view the colors of different materials and provide inspiration for material color design)

Leather Alternative ▼ CM ▼ All Category ▼ *Continue to add more labels*

Product

Material

Double-click the material/product image to enter the corresponding material information interface.

Material knowledge base board

1.All labels

Material Type ▼
formed material
decoration material
all materials
organic material
polymer
metal & other
inorganic material
composite

Material Form ▼
particle/powder
film
cloth
sheet
bulk
3d object

Waste Origin ▼
organic PIW
organic PCW
synthetic PIW
synthetic PCW

Year +
2016
2017
2018
2019
2020
2021

Market Availability ▼
yes
no

EM / CM ▼
experimental
commercial

Color ▼
white
black
grey
yellow
red
green
blue
purple
brown

Materials for Similar Purpose ▼
metal
plastic
wood
glass
ceramic
soft material
coating

Product Category ▼
household product
architecture & interior
packaging & disposable product
furniture
others

Transparency ▼
opaque
translucent
transparent
optical quality

Reflection ▼
dead matte
eggshell
semigloss
gloss
mirror

Pattern ▼
2D
3D
fine
medium
coarse

Material Trend

2.The "x axis" and "y axis" buttons allow the materials to be arranged in a coordinate axis manner according to the set characteristics. For example, finding a opaque plastic with glossy finish.

3."Color system button" make material search results organize in Practical Color or Coordinate System. The system is based on the HVC (Hue/Value/Chroma) to change the scale, which is conducive to the color selection, matching and other color design works with material.

4.Cancel the above arrangement and return to the default grid layout (as shown on the left)

Figure 60 Material knowledge base access interface design and function introduction

4.4.2 Part 2: Material Exploration Module

Material Exploration Module

The Material Exploration Module is a built-in design tool in the database, which is used to support product designers or CMF designers to use existing resources in the database or import external contents to build visual presentations such as recycled material mood boards, trend maps etc. to aid product development (Figure 61). The visual board building canvas is inspired by the Milanote tool, where the user can layout and note the inspiration images according to the project requirements.

When the designer has created a certain number of images in canvas, click the “match button” in the right toolbar, and then click the visual element in canvas that you want to match, the system will detect the color, shape and other visual information of the current visual element and match the cases of recycled materials/products with similar quality in database, and display them in the material inspiration board (Fig. 62). Further, designers can filter them based on the specific needs according to the top label (for example, only show products made from recycled materials in a certain industry, specific recycled material color, etc.). When the mouse is close to the images in the material inspiration board, the product description and CMF element information will be displayed for designers to review, and images can also be directly dragged onto the canvas as a visual element for constructing a mood board.

In addition, the module supports designers to store external product/material cases in an image format to support the generation of their own CMF material inspiration library, this information could also be loaded into the material inspiration board to provide designers with a CMF design inspiration library containing recycled materials. To do this (Figure 63), firstly selecting the label tool in the right toolbar, clicking on the image you want to store from the canvas, then the label editing panel pops up, the designer can selectively fill in the CMF information about this image according to the preset information framework, clicking “Save to...”, assigning a storage path on your computer, and then saving. As it is based on the preset information framework, by checking the box to load the personal database, the image could be loaded into the material inspiration board to support designers' inspiration search, material selection and other design practices.

By designing this tool based on a visual and inspired search logic, we hope that the sensorial attributes of the recycled material will be of interest to the designer and make it easier to search for the appropriate recycled material based on their hand projects. At the same time, designers can share the content of the visual board which can enter the material inspiration board so that it can be accessed by others for inspiration.

The interface is divided into three main sections:

- Left Sidebar (Material knowledge base):** Contains filters for material selection. At the top, there are dropdowns for "All Materials" and "Green Hue". Below these are buttons for "Material Type", "Material Form", "Waste Origin", "Materials for Similar Purpose", "Market Availability", "EM / CM", "Color", "Transparency", "Reflection", "Pattern", "Product Category", "Material Trend", and "Year". A "Drop-down label collection box" is also present.
- Central Canvas (Visual board building canvas):** Displays a "Mood Board for Gen Z" with a target user description: "Target user: Young girl, Gen Z, Newcomers in the workplace Office environment, things around, lifestyle". Below the mood board are three material cards, each with a color swatch and a label: "HSV 55, 15, 88" (labeled "Tone on tone"), "Natural adhesive" (labeled "Grass waste"), and "Pattern grade: Coarse 2.5D Pattern".
- Right Panel (Image label editing window):** Contains a form for editing product information. It includes fields for "Product name/Developer" (Svilen Gamolov), "Description/note", "Product category" (Furniture), "Type of material made" (Composite), and "Material name" (Adhesive laminated wood). It also has sections for "Manufacturing and finishing process" (Hot bending / Painting), "Market availability" (No Concept design), and "Other images". A "Color swatch" section is at the bottom. A "Delete" button is located at the bottom right of the panel.

Annotations and numbered steps are provided on the right side of the interface:

1. This area is the material inspiration board. Here, the materials/product images in the database are displayed in pinterest-like format. Contents presented are determined by top label loaded. The images can be dragged into right visual board building canvas by holding down and dragging the mouse.
2. Click "Add label", then click a image in the canvas, image label editing window will pop up. Users could edit image information presented above, and save it in the database personal folder. Tagged images could be loaded into material inspiration board, belongs to private material resource created by designers.
3. Add text
4. Import external pictures to the canvas
5. Edit font style
6. Edit font style
7. Click on one of images in the inspiration board, it will automatically become larger with highlight display. There are four boxes below the image, namely Color, Material, Finishing, Pattern. Click on one of the box, corresponding contents with data tags will present. Double-click any box to enter the knowledge base module corresponding to the material to obtain more detailed material information.

Figure 61 Material exploration module interface composition

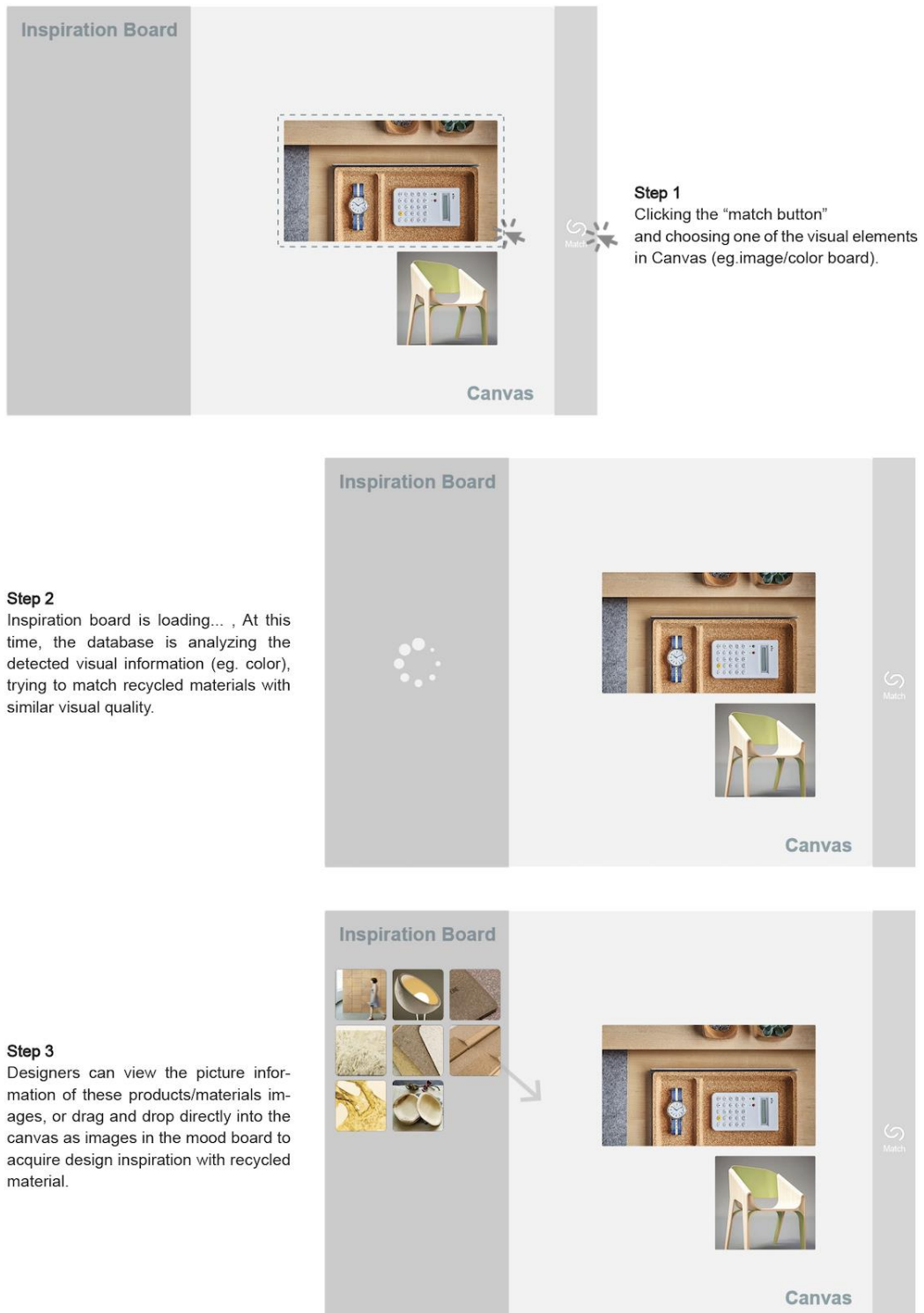
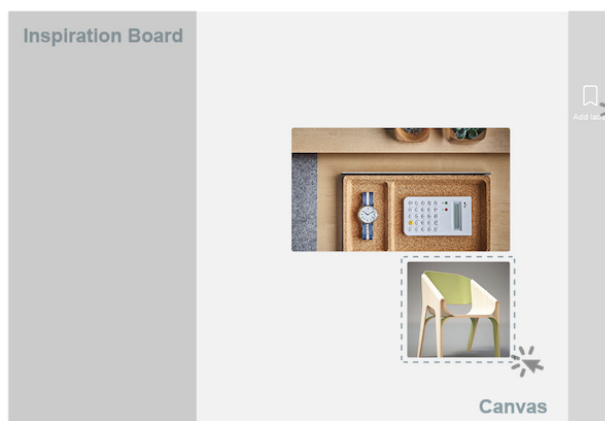
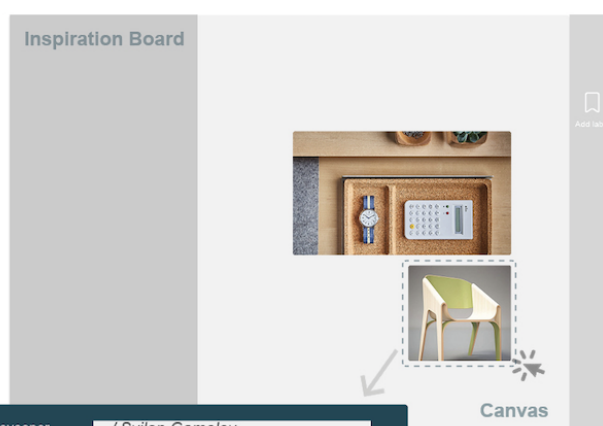


Figure 62 "Match button" function



Step 1
Clicking the “add label”
and selecting the image you want to
store from the canvas.

Step 2
The label editing panel pops up. The
designer can selectively fill in the CMF
information about this image according
to the preset information framework.



	Product name/Developer	- / Svilen Gamolov
	Description/note	
	Product category	Furniture
	Type of material made	Composite
	Material name	Adhesive laminated wood
Manufacturing and finishing process		Market availability
Hot bending / Painting		No Concept design
Color switch (could be automatically generated or customized editing)		Other images
		Save to...

Step 3
clicking “Save to...”, assigning a stor-
age path on your computer, and then
saving. you can form your own CMF
material/product inspiration board.

Step 4
By checking the box to load the person-
al database, the image could be loaded
into the material inspiration board.

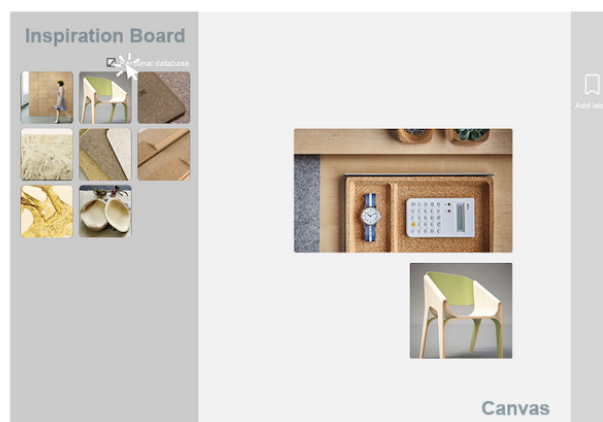


Figure 63 “Add label” function — personal databse creation

Application: A hypothetical project – material selection for built-in drawer of monitor holder

For better explanation of the status of tool usage, a hypothetical project is implemented. Through such a project case, show how the material exploration module encourages designers to introduce recycled materials into the project at hand.

Project goals:

Definding a trendy material with catchy color for built-in drawer of monitor holder which is designed for young girls of Gen Z. The material is matched with light-colored beech wood, which is lightweight for flexible movement.

The drawer is used to store small items on the desktop, stationery, etc. Inside has a guiding partition that is not very noticeable.

Product specification:



Findings:

Through the CMF element analysis of competing products and target user mood board insight, it is finally determined that the matcha green surface color with a fine graininess that echoes the light beech wood pattern, emphasizing the quality of the product details.

Through setting search labels such as material color and market availability, browsing the material inspiration board and finding that different levels of ground cereal/vegetable waste combined with natural binders can be used to obtain similar visual effect with more natural sense by compression molding, also enables produce relatively complex shapes and have adjustable strength. The surface color can be controlled through the dyeing process (Figure 64).

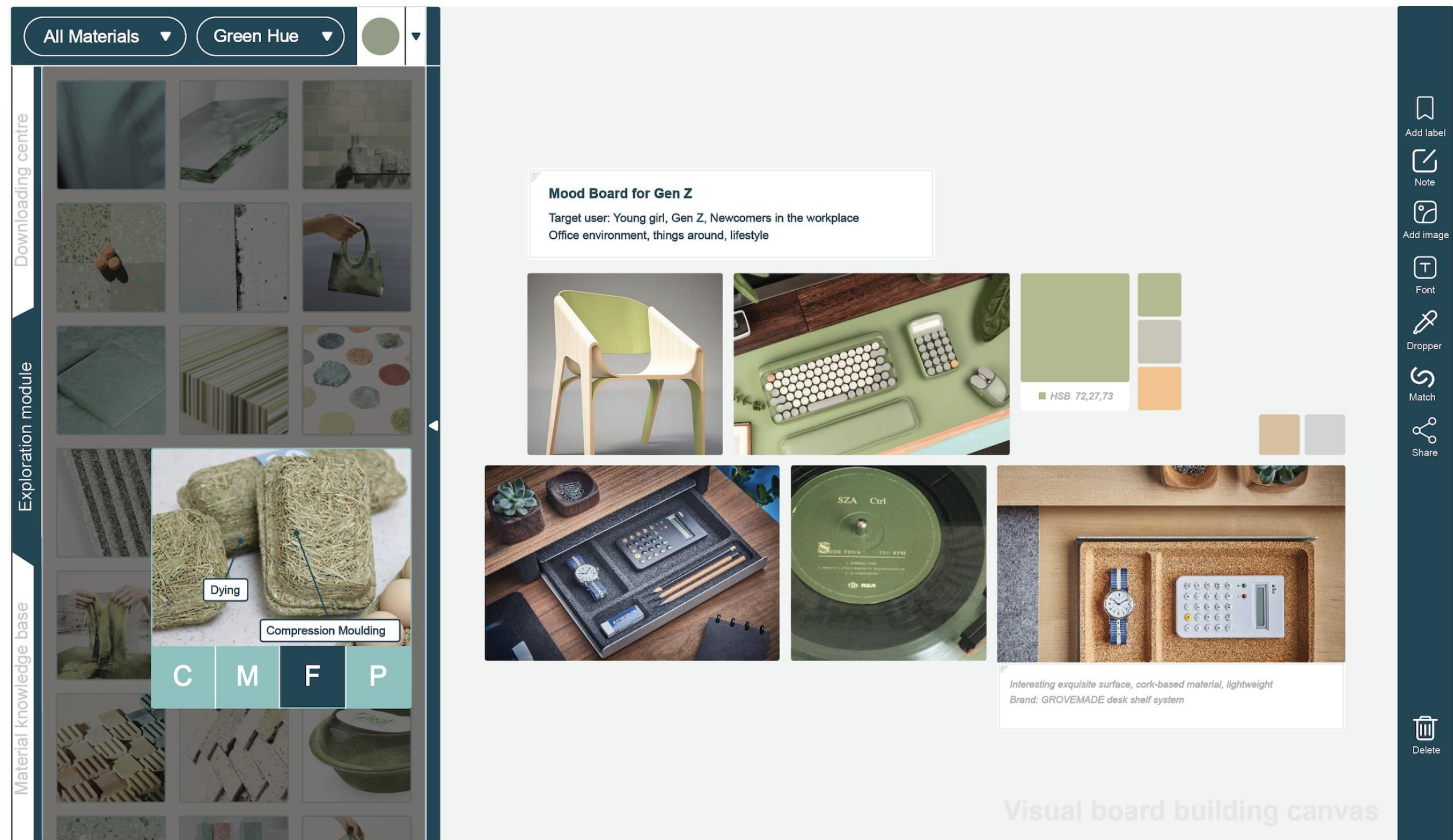


Figure 64 Material exploration module use status based on a hypothetical project

4.4.3 Part 3: Downloading Centre

The Downloading Centre is designed to provide support for rendering simulations, where material 2d maps and 3d pattern models are created based on recycled material images using Photoshop, 3dmax and other software, loading them into database to provide material files for designers to render. Both materials and finishing process are considered here, containing both mapping and modelling material files.

1. Texture maps in JPEG format (here the Keyshot rendering software is used as an example, containing 3 types of maps: color maps, specular maps, bump maps)
2. 3D pattern model in OBJ format (when the surface pattern of the material is obvious 3D effect, the pattern model could be used to complete the fine model creation)

Some presettled texture maps and models are created by the author, also users can upload and share their own maps and models under Creative Commons licenses.

Chapter 5 Discussion and Conclusion

This thesis studied the relationship between the novel recycled materials and product design, CMF practice, and material selection activity. Creating a recycled material database which encourages to take inspiration from such materials and apply them to the project at hand was created. This is a process of investigating the application of recycled materials in the field of product design. It is determined that there are already a large number of recycled materials with design attractiveness and excellent sustainable quality. The proposed database organizes and presents the information of these materials to designers in a creative and visual way, providing them with information on the potential for recycled materials to become an alternative material for the project at hand.

Compared with the existing material database, it has the following advantages:

- 1) Focusing on the information associated with recycled materials in product design, and providing knowledge and insights on recycled materials to promote product designers or CMF designers to use and explore them. As examined in the case study in Chapter 2, the composition of recycled materials, manufacturing technology, and the potential for application in product design and material exploration are reviewed. In addition, the database strengthens the relationship between material attribute and processing technology, and intuitively provides designers with the possible material physical and sensorial property changes of the material. The introduction of materials experiments, material trends, and application advantages provides designers with a more comprehensive view of the application of recycled materials.
- 2) With built-in design tools, it assists product designers or CMF designers to discover design opportunities for introducing recycled materials during design practice. This means that the database is not only for designers to retrieve relevant material information, but can also participate in the implementation of design activities such as mood boards and trend chart building. Therefore it encourages designers to explore more application opportunities of recycled materials based on the features of the project at hand, this form breaks the traditional database storage-retrieval-read database model, but emphasizes that the database is also a inspired tool to material finding, thereby encouraging more designers to use it.
- 3) The color element-oriented material information display mode takes into account the visual reasoning of the designer when carrying out the project at hand, and brings the designer a deeper material/product visual sensory insight; hence, it better support the designer to apply these materials in actual projects, such as material color matching, color area adjustment, etc.
- 4) Finally, downloading center stores the texture maps and pattern models of recycled materials support the designer's quick simulation and test of the product design.

However, we should also admit that the current database has shortcomings. Firstly, the database has not been tested in practical applications, so its effectiveness is only affirmed in theory at present. This is because the database requires a considerable amount of material/product cases to be filled before starting the test. This will be a huge collection and sorting project that cannot be completed in a thesis. Therefore, a future task could be to prepare and load more case information based on the structure in the database designed in this paper to support testing in designers. In addition, it has strong simulation for the visual characteristics of the material in the database. For example, the color property of the material depends on the color information of the electronic picture corresponding to the material, not the color of the material itself. This can, to some extent, cause uncertainty in terms of actual product landing (the actual material of the product is not consistent with what is shown on the screen). Therefore, one method is to use the existing digital color reading platform developed based on the spectrometer principle to measure the visual quality of recycled materials. However, it is also a challenge to provide designers with the complicated and uncertainty of the surface of recycled materials in a relatively consistent visual presentation, or an offline sample library could be built based on locally recycled material resources to make the surface quality of the material more effective and direct to interact with the designers. Finally, most of the content in the case study is directly derived from the website description, and not directly in contact with the material/product itself. Therefore, some content about sensorial evaluation is only based on the multi-image displayed by the creator, which will affect the accuracy of evaluated content. The evaluation of material considerations in CMF design is only based on relevant theories, tutorials, project presentations. The designer's investigation of material considerations in actual CMF design activities is not carried out, so the information collected has certain limitations.

In general, the database proposes a new inspired, creative format to organize recycled material information to provide a bridge between novel recycled materials and the designer's project at hand. It is highly interactive, allowing designers to gain insight into the use of recycled materials, conduct material exploration activities based on the project at hand, build their own material inspiration library and support downloads, share recycled material mapping, texture models and other design materials to encourage designers to use recycled materials in product design. In the future, it is expected that a complete database prototype could be designed for testing, and the deficiencies in the database can be better corrected based on the feedback data.

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







































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































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APPENDIX 1. RECYCLED MATERIAL CASE STUDY FORM: MATERIAL - PRODUCT

Raw material (name/feedstock)	Developer/Year	Availability	Reference link	Manufacturing (recycling method/stock form/scale)		Products (name/application area)	Industry	Material advantages (technical/aesthetic/sustainable)		
 Jeans on the wall, Textile on the wall / Textile waste(eg.recycled jeans fibers) or biobased textile fibers, Biobased glue	Denimtex, Netherlands / 2017	Yes	https://www.denimtex.nl	Physical recycling / Paste		Textile plaster / Surface treatment(eg.decoration) for wall or ceiling	Architecture & interior	TECHNICAL: //acoustic absorption-good //chemical resistance-good //weather resistance-poor	AESTHETIC: //customized color and unique fiber texture //Tactile-soft, cool tem. //Visual-matte, coarse texture	SUSTAINABLE: //renewable-yes //recyclable-yes //biodegradable-no
 Colorful HDPE Plastic Sheet-Origins Solids / Uncolored post-consumer recycled polyethylene resin(HDPE), color pigment	YEMM & HART, USA / 2005	Yes	https://yemmhart.com	Physical recycling / Sheet		HDPE sheet / Molded products(eg.vanities and countertops), Toilet stalls, Structure part	Architecture & interior, furniture	TECHNICAL: //chemical resistance-good //UV resistance-poor	AESTHETIC: //customized color or artistic texture //Tactile-hard, medium tem. //Visual-satin, mottled spots texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Tire Veneer / Rubber waste(buffings) from tire renovation , Virgin EPDM rubber granules, Urethane	YEMM & HART, USA / 2005	Yes	https://yemmhart.com	Chemical recycling / Layer		Tire Veneer / flooring material, consumer products, vibration dampeners and furniture surfaces, sports & recreation, animal housing, Cargo & Truck Mats	Architecture & interior, furniture, consumer products	TECHNICAL: //durability-good //impact resistance-good //acoustic absorption-good	AESTHETIC: //black background with high saturation color dot //Tactile-soft, warm tem. //Visual-satin, mottled spots texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Bio-Glass / Post-consumer recycled glass from consumer bottles and industrial glass	COVERINGSETC, USA / 2010	Yes	https://www.coveringsetc.com	Chemical recycling / Slab		Glass blank / Counters, Vanities, Back Splash, Walls, Shower Walls, Exterior Façade, Floors (R10), Industrial Design	Architecture & interior, furniture, daily necessities	TECHNICAL: //scratch resistance-good //UV resistance-good //durability-good	AESTHETIC: //Optional aesthetic pattern //Tactile-hard, cool tem. //Visual-satin, texture with specific semantics	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Ash-Grey Eco-Terr / Main stone waste mixed with cement, fly ash	COVERINGSETC, USA / 2010	Yes	https://www.coveringsetc.com	Physical recycling / Slab		Stone slab / Flooring, Outdoor Terrace, Pool, Pavers, Counters, Vanities, Walls, Exterior Façade, Furniture, Industrial Design	Architecture & interior, furniture, daily necessities	TECHNICAL: //scratch resistance-good //bacterial resistance-good //durability-good	AESTHETIC: //Optional surface roughness, texture //Tactile-hard, cool tem. //Visual-glossy, texture with optional color	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Eco-Cem / Main cement waste mixed with fly ash, Recycled wood pulp	COVERINGSETC, USA / 2010	Yes	https://www.coveringsetc.com	Physical recycling / Sheet and Tile		Tiles / flooring, interior/exterior cladding, furniture or worktops	Architecture & interior, furniture, daily necessities	TECHNICAL: //scratch resistance-good //surface air permeability-yes //durability-good	AESTHETIC: //optional color with natural finish //Tactile-hard, cool tem. //Visual-matte, patina aging, warm look texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Eco-Gres / Unglazed porcelain (contains 36% pre-consumer recycled content)	COVERINGSETC, USA / 2010	Yes	https://www.coveringsetc.com	Physical recycling / Tile		Tiles / Tiles for wall	Architecture & interior	TECHNICAL: //impact resistance-good //slip resistance-good	AESTHETIC: //optional color with natural finish //Tactile-hard, cool //Visual-matte, medium texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Bio-Luminum / Recycled aircraft aluminium	COVERINGSETC, USA / 2016	Yes	https://www.coveringsetc.com	Physical recycling / Tile		Tiles / high-traffic flooring, high-end wall treatments	Architecture & interior	TECHNICAL: //strength-great //chemical resistance-good	AESTHETIC: //Tactile-hard, cool tem. //Visual-glossy, medium texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Pretty plastic / Plastic waste(eg.PET,HDPE,PE from building sector)	Pretty Plastic, Netherland / 2017	Yes	https://www.prettyplastic.nl	Physical recycling / preset cladding material-tile		Tiles / Building facade covering material	Architecture & interior	TECHNICAL: //durability-good //weight-light	AESTHETIC: //preset color with 9 grey scales //Tactile-hard, warm tem. //Visual-matte, smooth texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 OESTERPLAT / Marble and oyster shells waste, cement binder	D'WERKPLAATS, Netherlands / 2018	No	https://materialdistrict.com/material/oester-plat	- / Slab and Tile		Tiles / -	Architecture & interior	TECHNICAL: //durability-good //chemical resistance-poor	AESTHETIC: //Random texture dotted with oyster shell surface //Tactile-hard, cool tem. //Visual-variable, medium texture	SUSTAINABLE: //renewable-no //recyclable-no //biodegradable-no
 REPREVE FIBRES & FABRIC / PET bottles waste	Repreve, USA / 2018	Yes	https://materialdistrict.com/material/repreve-fibres-fabric	Physical and chemical recycling / Cloth		Textile / various features of fabrics for athletic and fashion apparel and more	Textiles	TECHNICAL: //air permeability-variable //water repellency-variable //scratch resistance-good	AESTHETIC: //Tactile-soft, warm tem. //Visual-variable glossiness, variable texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 SilicaStone / Glass and ceramics waste	Alusid, UK / 2018	Yes	https://www.alusid.co.uk	- / Slab and Tile		Tiles / tiles and slabs, for use in both interior and exterior design schemes	Architecture & interior, furniture	TECHNICAL: //UV-resistance-good //scratch resistance-good	AESTHETIC: //Slightly and controllable color and texture //Tactile-hard, cool tem. //Visual-variable glossiness, variable texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Corktex / High tenacity polyester thread, Cork waste, Tire waste	Corktex, Spain / 2017	Yes	https://www.corktex.com	- / Cloth, Sheet		Fabric / lining floors, walls and ceilings	Architecture & interior	TECHNICAL: //bacterial resistance-good //soundproofing-high //compression resistance-light	AESTHETIC: //Warm color with nature finish //Tactile-resilient, good thermal comfort //Visual-matte, medium texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Plastic stone tiles / Postconsumer plastic waste	ENIS AKIEV, Germany / 2018	No	http://cargocollective.com/enisakiev/PLASTIC-STONE-TILES	Physical recycling / Tile		Tiles / -	Architecture & interior	TECHNICAL: //UV resistance-good	AESTHETIC: //rock-like texture(like plastiglomerate surface) //Tactile-hard, medium tem. //Visual-matte, smooth texture	SUSTAINABLE: //renewable-no //recyclable - //biodegradable-no
 Recycrom / textile fibres from used clothing and manufacturing waste	Denimtex, Germany / 2017	Yes	https://recycrom.com	Chemical recycling / Powder		Dyes / dye for fabrics and garments made of cotton, wool, nylon or any natural fibre and blend.	Textiles	TECHNICAL: //UV-resistance-good //chemical resistance-poor //fire resistance-poor	AESTHETIC: //Tactile-cool tem. //Visual-matte, variable texture	SUSTAINABLE: //renewable-no //recyclable - //biodegradable-no
 013 Denim / Recycled denim yarn(from jeans waste), organic cotton yarn	Wolkat, Netherlands / 2017	Yes	https://wolkat.com/en/projects/project-1	Physical recycling / Cloth		Textile / Denim fabric for garments, shoes, bags	Textiles	TECHNICAL: //UV resistance-good //chemical resistance-poor //weight-light	AESTHETIC: //denim color mixed uneven fibre impurities //Tactile-soft, warm tem. //Visual-matte, smooth texture	SUSTAINABLE: //renewable-yes //recyclable-yes //biodegradable-no
 Spinneybeck's Beller Collection cork tiles / Industrial cork waste, resin	Spinneybeck, USA / 2019	Yes	https://www.spinneybeck.com	Physical recycling / Slab		Tiles / Surface treatment(eg.decoration/sound absorption system) for wall or ceiling	Architecture & interior	TECHNICAL: //acoustic absorption-good //chemical resistance-good //weight-light	AESTHETIC: //nature finish with granular surface //Tactile-resilient, warm tem. //Visual-matte, variable texture	SUSTAINABLE: //renewable-yes //recyclable-yes //biodegradable-yes
 Refil, fully recycled 3d printer filament / Inside of old refrigerators waste(HIPS), dashboard waste(ABS), PET package	Refil, Netherlands / 2017	Yes	https://betterfuturefactory.com/portfolio_page/refilament	Chemical recycling / filament		3d printer filament / prototyping making	-	TECHNICAL: //surface can be glued and painted //mechanical property-good //weight-light	AESTHETIC: //black and white color //Tactile-hard, medium tem. //Visual-matte, medium texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Ecolution Recycled Nylon Fabric / Recycled polyamide from postindustrial waste products	Jou Jou Fish, Taiwan / 2019	Yes	https://materialdistrict.com/material/ecolution-recycled-nylon-fabric	- / Cloth		Fuctional Fabric / -	Textiles	TECHNICAL: //material with micro-porous membrane (functional performance 15K/10K) //UV and scratch resistance-good	AESTHETIC: //renewable-no //Tactile-soft, warm tem. //Visual-matte, smooth texture	SUSTAINABLE: //renewable-no //recyclable-no //biodegradable-no
 Plasticiet / discarded plastics (LDPE-HDPE, PS, ABS)	PLSTCT, Netherlands / 2019	Yes	https://materialdistrict.com/material/plasticiet	Physical recycling / Slab		Plastic sheet / furniture making, interior design, displays and purely decoratively	Architecture & interior, furniture	TECHNICAL: //UV and scratch resistance-good	AESTHETIC: //random surface with rock-like pattern //Tactile-hard, medium tem. //Visual-variable glossiness, smooth texture	SUSTAINABLE: //renewable-no //recyclable-- //biodegradable-no
 Industrial Craft / plastic waste streams associated with CNC fabrication (eg. polyurethane foam dust from	Charlotte Kidger, UK / 2019	Yes	https://www.charlottekidger.com/samples	Physical recycling / Slab		Composite slab / Customized making(eg.sculpture,vassels etc)	Furniture, daily necessities	TECHNICAL: //UV resistance-good	AESTHETIC: //porous appearance with optional color //Tactile-soft, warm tem. //Visual-matte, variable texture	SUSTAINABLE: //renewable-no //recyclable-- //biodegradable-no
 Raytent fabric / Recycled acrylic fabric	Filii Giovanardi, Italy / 2019	Yes	https://materialdistrict.com/material/raytent-recycled-acrylic-fabric	Physical recycling / Cloth		Textile / Outdoor furniture, garden and pool furniture, in particular cushions for sun loungers, sofas, chaise longues and chairs, decorative panels, pergolas and fixed structures.	Architecture & interior, furniture, daily necessities	TECHNICAL: //water-repellent-good //water-repellent-good //light fastness-good	AESTHETIC: //Tactile-soft, cool tem. //Visual-matte, smooth texture	SUSTAINABLE: //renewable-no //recyclable-- //biodegradable-no
 TMF Valencia recycled glass / Glass waste(eg.discard window glass)	The Mosaic Factory, Netherlands / 2019	Yes	https://materialdistrict.com/material/tmf-valencia-recycled-glass	Chemical recycling / Tile		Tiles / Flooring	Architecture & interior	TECHNICAL: //weather resistance-good //UV and scratch resistance-good	AESTHETIC: //low purity colors with glossy/matte surface //Tactile-hard, cool tem. //Visual-variable, smooth texture	SUSTAINABLE: //renewable-no //recyclable-- //biodegradable-no
 Remake ceramics / Broken pieces of ceramics	Fabrique Publique, Netherlands / 2019	Yes	http://hanneke-deleeuw.com/remake-ceramics-nature-calling	Chemical recycling / Slab		- / Consumer products (eg.tableware, vase)	Daily necessities	TECHNICAL: //UV and scratch resistance-good	AESTHETIC: //low purity colors with (un)glazed surface //Tactile-soft, cool //Visual-matte, coarse texture	SUSTAINABLE: //renewable-no //recyclable-- //biodegradable-no
 C-Slurry / Steel slag, lime mud, primary sludge from the wastewater treatment plant and wood	C-Hub & LiLinLab, Taiwai / 2019	Yes	https://materialdistrict.com/material/c-slurry	Chemical recycling / Slab		- / Wall construction	Architecture & interior	TECHNICAL: //UV and scratch resistance-good //weather resistance-good	AESTHETIC: //Tactile-hard, cool tem. //Visual-variable glossiness, variable texture	SUSTAINABLE: //renewable-no //recyclable-- //biodegradable-no
 Circular Concrete Cityscapes / Waste from urban mining	Studio Wae, Netherlands / 2019	Yes	https://studiowae.nl	Chemical recycling / Tile		Tiles / Surface treatment(eg.decoration) for wall or ceiling	Architecture & interior	TECHNICAL: //drainage-good //anti slip-good //durability-good	AESTHETIC: //Tactile-hard, cool tem. //Visual-matte, coarse texture	SUSTAINABLE: //renewable-no //recyclable-- //biodegradable-no
 Experimental Terrazzo / Waste material from construction(eg.brick/wood/metal etc.)	Huguet, Spain / 2019	Yes	https://huguetmallorca.com/en/products/terrazzo	Physical recycling / Tile		Tiles / Surface treatment(eg.decoration) for wall or ceiling	Architecture & interior	TECHNICAL: //UV and scratch resistance-good //chemical resistance-good	AESTHETIC: //low purity color mix with random dots //Tactile-hard, medium tem. //Visual-satin, smooth texture	SUSTAINABLE: //renewable-no //recyclable-- //biodegradable-no

APPENDIX 2. RECYCLED MATERIAL CASE STUDY FORM: MATERIAL - PRODUCT

Raw material (name/feedstock)	Developer/Year	Availability	Reference link	Manufacturing (recycling method/stock form/scale)	Products (name/application area)	Industry	Material advantages (technical/aesthetic/sustainable)		
 Hidden beauty / waste from the slaughter industry(eg.animal offal, bone, etc.), resin	Clemence Grouin-Rigaux, UK / -	No	https://www.clemencegrouinrigaux.com/	Physical recycling / Viscous liquid	 Paint / Surface treatment with a variety of products, such as stool	Furniture, daily necessities	TECHNICAL: -	AESTHETIC: //black color with unique crack texture //Tactile-hard, medium tem. //Visual-glossy, medium texture	SUSTAINABLE: //renewable-yes //recyclable-no //biodegradable-no
 Fruit/leather / left-over fruit, animal hide waste	Fruit/leather Rotterdam, Netherlands / -	Yes	https://fruitleather.nl/	- / Cloth	 Leather / footwear, fashion accessorie, interior and furnishing industry.	Architecture & interior, textiles	TECHNICAL: -	AESTHETIC: //black color with leather-like texture //Tactile-soft, warm tem. //Visual-matte, coarse tex.	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 That's Caffeine / waste coffee grounds, bio-resin	Atticus Durnell, UK / -	No	https://www.atticusdurnell.com/thats-caffeine	- / Sheet	 Lighting, vase and other consumer products	Furniture, daily necessities	TECHNICAL: //water resistance-good //heat resistance-good	AESTHETIC: //dark brown background with feel of granite //Tactile-hard, warm tem. //Visual-glossy, medium texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-yes
 Glass Form / recycled consumer glass and reclaimed eggshells	Steven Akoun, USA / 2010	No	https://stevenakoun.com/5/	Chemical recycling / Slab	 ACOUSTIC WALL TILES, humidifier, lamp, cup, knife sharpening whetstone, vases	Architecture & interior, furniture, daily necessities	TECHNICAL: //sound absorption-good //heat insulution-good //water absorption-good //light transmission-good	AESTHETIC: //Foamed surface with optional color //Tactile-hard, cool tem. //Visual-matte, coarse texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 LOZI / sawdust, bio-resin	LOZI, UK / 2010	No	https://www.lozide-signs.com/new-blog/2020/4/23/developing-our-bio-resin-and-waste-sawdust-surface	Physical recycling / Pasta	 Table top	Furniture	TECHNICAL: -	AESTHETIC: //warm dyes with the light yellow of sawdust //Tactile-hard, warm tem. //Visual-matte, medium texture	SUSTAINABLE: //renewable-yes //recyclable-no //biodegradable-no
 Freitag / waste truck canvas	Freitag, Switzerland / 1993	Yes	https://www.freitag.ch/en	Physical / Cloth	 Fabric/bags, wallet, notebook cover, key chain	Daily necessities	TECHNICAL: //shock-resistant-good //water resistance-yes //durability-good	AESTHETIC: //optional pattern //Tactile-hard, cool tem. //Visual-matte, aging surface and texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Recycled PET blend / polyester, recycled PET, other eco-friendly cotton	Waste2wear, Netherlands / 2010	Yes	https://www.waste2wear.com/	Physical recycling / Cloth	 Fabric/interior textiles, apparel, bags	Textiles	TECHNICAL: -	AESTHETIC: //optional color with high-quality finish //Tactile-optional, warm tem. //Visual-optional, smooth texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Qmilk / spoiled milk	Qmilk, Germany / 2018	Yes	https://www.qmilkfiber.eu-/lang=en	Chemical recycling / Cloth	 Fabric / apparel, bed linings	Textiles	TECHNICAL: //increased silk feel and strength, improved original fiber property	AESTHETIC: //Tactile-soft, warm tem. //Visual-matte, smooth texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-yes
 Orange fiber / citrus juice by-products, other fibre	Orange fiber, Italy / 2017	Yes	http://orangefiber.it/en/	Chemical recycling / Cloth	 Fabric / apparel	Textiles	TECHNICAL: //moisture management-good //breathability-good	AESTHETIC: //Tactile-soft, warm tem. //Visual-matte, silk-like texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Amazonian Fish Skin Fabrics / fish skin waste	Oskar Metsavaht, Brazil / 2018	No	https://www.trendhunter.com/trends/amazonian-fish	Chemical recycling / Cloth	 Tiles / -	Architecture & interior	TECHNICAL: -	AESTHETIC: //Black color, unique fish skin texture //Tactile-hard, warm tem. //Visual-variable, leather-like texture	SUSTAINABLE: //renewable-yes //recyclable-no //biodegradable-yes
 “Soft Rush” foam material / Pith seperated from fibers of soft rush	Don Kwaning, Netherlands / 2018	No	https://materialdistrict.com/artide/medulla-weed-furniture/	Physical recycling / Sheet	 Plant foam sheet / packaging material and furniture	Packaging & disposable products, furniture	TECHNICAL: //changable density of foam //lightweight //shock-resistant-good //Thermal insulation-good	AESTHETIC: //Foam-like surface //Tactile-soft, warm tem. //Visual-matte, variable texture	SUSTAINABLE: //renewable-yes //recyclable-yes //biodegradable- -
 Stonethica / Waste from stone processings also in combination with heterogeneous materials, resin	Stonethica, Italy / 2018	Yes	https://www.stonethica.com/classic-material/	Physical recycling / Slab and sheet	 Tiles / tiles and slabs, for use in both interior and exterior design schemes, Furniture board	Architecture & interior, furniture	TECHNICAL: //UV-resistance-good //scratch resistance-good	AESTHETIC: //Random marble surface //Tactile-hard, cool tem. //Visual-variable glossiness, variable texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Ecosurfaces / Rubber waste (Vulcanized Composition Rubber)	Ecosurfaces, USA / 2017	Yes	https://www.scorecommercial.com/Products/-Composed/ECOSurfaces	Chemical recycling / Sheet,Tile	 Rubber rolls and tiles / Rubber floors	Architecture & interior	TECHNICAL: //elastic modulars-higher//durability-good //slip resistant-good	AESTHETIC: //Dotted colorful choice //Tactile-resilient, warm tem. //Visual-matte, smooth texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Zantech / Recovered graphite powder	Alisea , Italy / 2018	No	https://www.perpetua.it/oggetti-perpetua-la-matita?lang=en	Chemical recycling / Powder	 Perpetua / Recycledge graphie waste	Architecture & interior	TECHNICAL: //durability-good //shock resistance-good	AESTHETIC: //Tactile-cool tem. //Visual-matte, variable texture	SUSTAINABLE: //renewable-no //recyclable- - //biodegradable-no
 Organoid / Different kind of nature waste from Alpine, ecological binding agent	Organoid, Austria/ 2017	Yes	https://www.organoids.com/en/about-us/what-does-organoid-mean/	Physical recycling / Sheet	 ORGANOID natural surfaces / wall decoration, flooring panels, acoustic elements, etc.	Architecture & interior	TECHNICAL: //durability-good //sound absorption-good	AESTHETIC: //nature surface //Tactile-warm tem. //Visual-matte, variable texture	SUSTAINABLE: //renewable-no //recyclable- - //biodegradable-no
 Potato Food Packaging / Starch, lettuce, fiber extracted from dehydrated potato peels	Simone Caronni, etc. Portugal / 2017	No	https://www.yankodesign.com/2018/09/10/potato-in-potato-packaging/	Chemical recycling / Paper	 Potato made paper / Ice-cream package, etc.	Packaging & disposable products	TECHNICAL: //edible	AESTHETIC: //Exaggerated fiber mechanism, pleated //Tactile-soft, warm tem. //Visual-matte, coarse texture	SUSTAINABLE: //renewable-yes //recyclable-yes //biodegradable-yes
 Tableware from wild leaf / fallen Indian areca palm leaves, resin	Wild life, USA / 2019	Yes	http://www.wildleafableware.com/index.html	Physical recycling / Slab	 Tiles / Surface treatment(eg.decoration/sound absoption system) for wall or ceiling	Architecture & interior	TECHNICAL: //acoustic absorption-good //chemical	AESTHETIC: //nature finish with granular surface //Tactile-resilient, warm tem. //Visual-matte, variable texture	SUSTAINABLE: //renewable-yes //recyclable-yes //biodegradable-yes
 Pineapple leaves fiber / Pineapple leaves waste	Pinatex, UK / 2015	Yes	https://www.ananas-anam.com/about-us/	Physical and chemical recycling / Fiber	 PLFA fabric / many kinds of textile, such as apparel, bag furniture surface treatment	Architecture & interior , furniture	TECHNICAL: //enhanced strength //abrasion resistance-good //water resistance-good	AESTHETIC: //leather-like material, rich pattern types //Tactile-hard, medium tem. //Visual-matte, medium texture	SUSTAINABLE: //renewable-yes //recyclable-no //biodegradable-no
 Sustainable feather-based insulation material / Waste feathers	Aeropower, UK / 2017	Yes	https://www.aeropowder.com/technology	Chemical recycling / Paper	 Package paper / package paper used in food or pharmaceutical deliveries	Textiles	TECHNICAL: //lightweight-good //thermal insulation-good	AESTHETIC: //Tactile-soft, warm tem. //Visual-matte, smooth texture	SUSTAINABLE: //renewable- - //recyclable- - //biodegradable- -
 denim fiber-based panel material / denim fibers	PLSTCT, Netherlands / 2019	Yes	https://trendland.com/towards-a-new-matter/	Physical recycling / Panel	 Modular partition blocks / Desktop partition	Architecture & interior, daily necessities	TECHNICAL: //lightweight-good //Sound absorbing-good	AESTHETIC: //Denim color coarse grained surface //Tactile-hard, medium tem. //Visual-matte, variable texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-yes
 Recycled PET felt wall-paper / PET waste	RTS-PREIDEL, Netherlands / 2020	Yes	https://materialdistrict.com/material/recycled-pet-felt-wall-cover/ https://www.rts-preidel.nl/vilt?lang=en	Physical recycling / Panel	 RTS acoustic panels / Customized wall surface treatment, furniture surface treatment	Architecture & interior, furniture	TECHNICAL: //Impact resistance-good //Sound absorbing-good //Durability-good	AESTHETIC: //Tactile-soft, warm tem. //Visual-matte, medium texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Bio-derived pigment powder / fruit and vegetable peels	Nicole Stjernsward, UK / 2019	Yes	https://vimeo.com/343860808	Physical recycling / Powder	 dye / Fabric dyeing for garments or carvans	Textiles	TECHNICAL: //Easy to save	AESTHETIC: //Vivid optional color	SUSTAINABLE: //renewable-no //recyclable- - //biodegradable-yes
 Sustonable engineered stone / PET bottles	Sustonable, Spain / 2014	Yes	https://www.sustonable.com/	Physical recycling / Sheet	 Customized sheet / desktop, partition, wall surface treatment	Architecture & interior, furniture	TECHNICAL: //weather resistance-good //UV and scratch resistance-good //chemical resistance-good	AESTHETIC: //mono or marble-like surface //Tactile-hard, cool tem. //Visual-variable, smooth texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-no
 Parblex™ Plastics [PBX] / Different kind of biomass waste	Chip[s] Board", UK / 2016	Yes	https://www.chipsboard.com/materials	Chemical recycling / sheet	 Parblex™ Plastics [PBX] Series / Glasses plate, construction supporting structure	Daily necessities , furniture, architecture & interior	TECHNICAL: //Machining and molding properties-good	AESTHETIC: //optional color: dark brown,lemon yellow //Tactile-hard, medium tem. //Visual-matte, smooth texture	SUSTAINABLE: //renewable-no //recyclable-yes //biodegradable-yes
 Foamy composite bio material / Sunflower crop waste	STUDIO THOMAS VAILLY, Netherlands / 2017	No	http://studiothomasvailly.com/project/sunflower-entreprise-4/	Chemical recycling / Slab	 Sunflower-based bio composite panel / Wall construction	Architecture & interior, furniture	TECHNICAL: -	AESTHETIC: //Tactile-hard, warm tem. //Visual-valiable glossiness, variable texture	SUSTAINABLE: //renewable- //recyclable- //biodegradable-yes
 Flash line / 100% recycled yarn and contains 86% recycled and biobased materials	Interface , Netherland / 2021	Yes	https://www.interface.com/EU/en-GB/collections/embodied-beauty	- / Tile	 Tiles / Carpet tile	Architecture & interior	TECHNICAL: //Fire resistance-good //UV and scratch resistance-good //chemical resistance-good	AESTHETIC: //Tactile-resilient, medium tem. //Visual-matte, medium texture	SUSTAINABLE: //renewable-no //recyclable- //biodegradable-no
 Dungse-based composite / Dungse waste	STUDIO CARBON AND STUDIO LINDEY CAFSIA, Netherland / 2019	No	https://www.dungse.com/	Chemical recycling / Panel or slab	 Tiles / alternative for traditional materials such as (virgin) wood, plastic and other stoney materials in construction, home products and accessories	Architecture & interior, furniture, daily necessities	TECHNICAL: //lightweight	AESTHETIC: //Tactile-hard, medium tem. //Visual-variable, variable texture	SUSTAINABLE: //renewable-yes //recyclable- //biodegradable-yes

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