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Upcycling food industry by-products. Bringing the circular economy to the attention of decision makers

Experimental degree thesis

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We need to Upcycle
to reach environmental, social,
and economic prosperity.

It is the right time to make a difference,
to start thinking circularly, in a systemic way.

It is the right time to preserve our natural resources and
make them available for everyone, forever.

It is the right time to innovate.

It is the right time to take action
since Every contribution counts.

It is the right time to upcycle.

Together only, we can make it!

Abstract

Food wastage represents a massive issue in today's society. It impacts the environment (e.g., climate change, resources depletion, biodiversity loss), society (e.g., food security), and the global economy. All the stakeholders could change systemically to transition towards the circular economy. Corporates must involve leadership, employees, suppliers, and consumers to build a more efficient and resilient system where waste and by-products generation is limited. The unavoidable waste could be valorized to new raw materials to reduce the environmental impact of their disposal. Food waste and by-products could preferably be reused as animal feed, upcycled to high added value compounds (e.g., biomolecules), recycled into low-value products (e.g., compost, and digestated from anaerobic digestion), and recovered as energy through incineration. Instead, the literature lacks environmental studies about food by-products reprocessed into new food formulations.

This thesis focuses on Barilla (the Italian food company since 1877) and its willingness to valorize by-products (e.g., bread crust), maximizing all aspects of sustainable development: economy, ecology, and social equity.

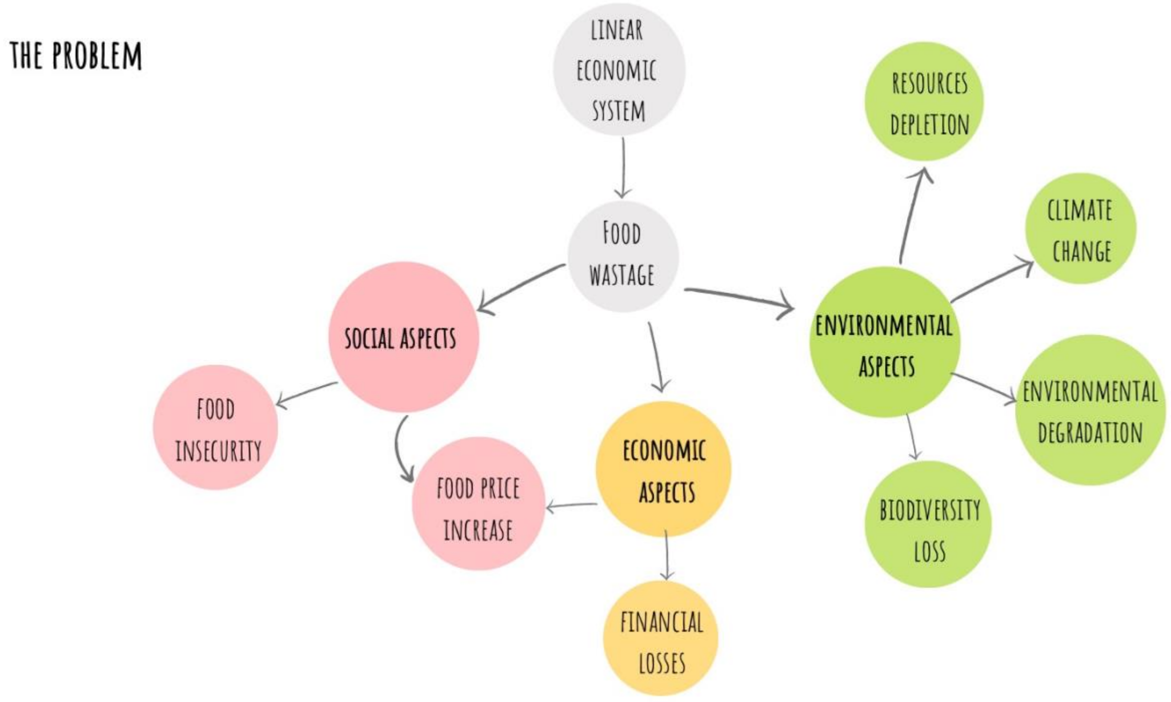
First, the author formed an Upcycling Team, an inter-functional group of voluntaries, to define Barilla's criteria for by-products valorization. Afterwards, the Team screened the possible bread crust valorization options (e.g., food product, beer, and animal feed production) using the Analytic Hierarchy Process (AHP), a decision-making tool that allows selecting the best alternative under conflicting criteria. The method's strength is the ability to judge the elements in pairs and use qualitative evaluation. The latter allows proceeding with the screening process faster, prerogative number one in the corporate's world. The AHP suggested that producing a food product (e.g., rusk) is the most sustainable option among the three. Indeed, it enhances the company's profit, people's well-being and benefits the environment.

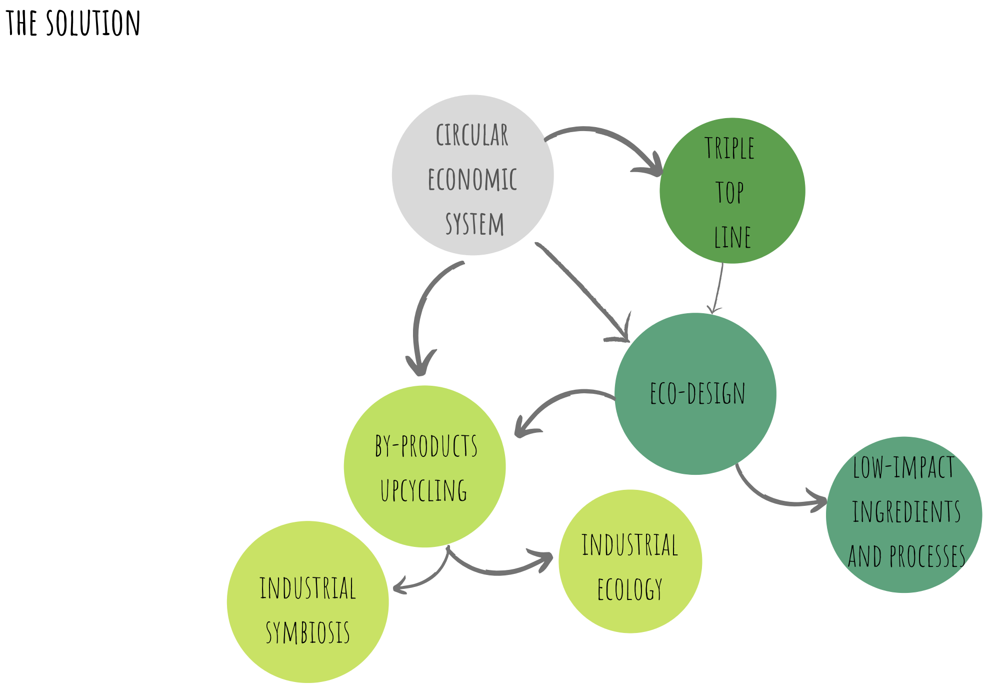
Furthermore, the author carried out a partial Life Cycle Assessment (i.e., from cradle to factory gate) to compare the global warming potential (GWP) of the production of upcycled rusks to animal feed accounting for the avoided production of the standard products. She demonstrated that producing upcycled rusks using 1 kg of bread crust results in greater net-reduction of greenhouse gas emissions than upcycled animal feed (- 0.35 kg CO2eq and - 0.27 kg CO2eq, respectively).

These findings contribute to filling the knowledge gap on the use of food-by-products reprocessed for new food products. Moreover, they confirm the results obtained qualitatively using AHP, providing quantitative insights. Furthermore, they may push Barilla to implement

an upcycled food product designed by adopting the eco-design approach to implement an environmentally sustainable food product from its raw materials to its end-of-life.

Graphical abstract





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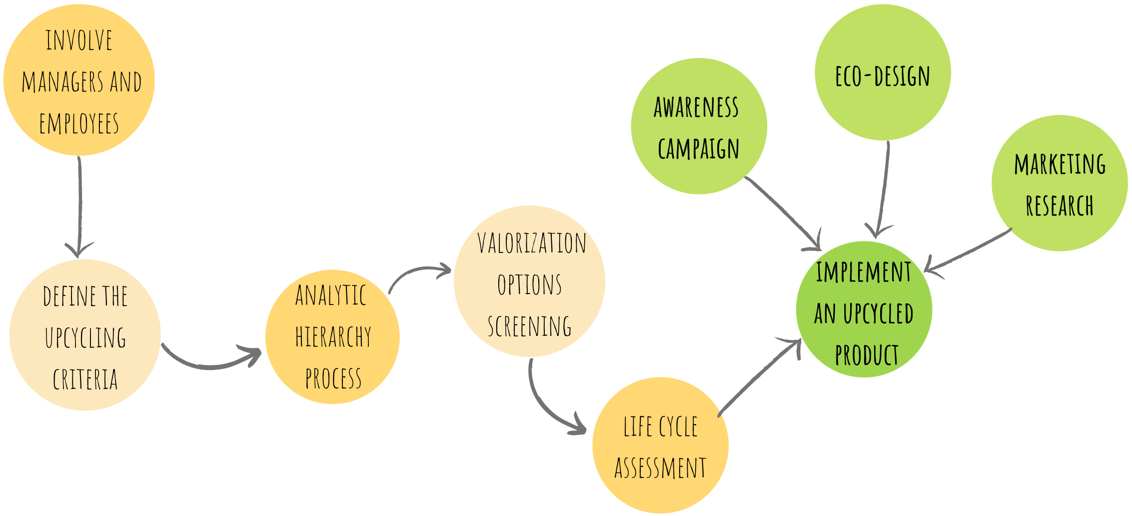

Summary

1. Introduction

1.1. The problem: food wastage

Our planet is experiencing unprecedented climate change and environmental degradation (Masson-Delmotte et al., 2021). Moreover, the material consumption is expected to double over the next thirty years (Borowski, 2020). Paradoxically, annual waste generation is forecasted to increase by 50% by 2050 (Kaza et al., 2018).

In this context, food production and food wastage are among the factors contributing to global warming, resources depletion (e.g., phosphorus, land, water), and biodiversity loss (Cordell et al., 2009). It is estimated that one-third of the total food produced each year is either lost or wasted throughout the Food Supply Chain (FSC)[1](Gustavsson et al., 2011). The reader can imagine that if food wastage were a country, it would be the third-largest greenhouse gas (GHG) emitter generating 4.4 Gt CO_2eq per year (Fig.1) (FAO, 2013).

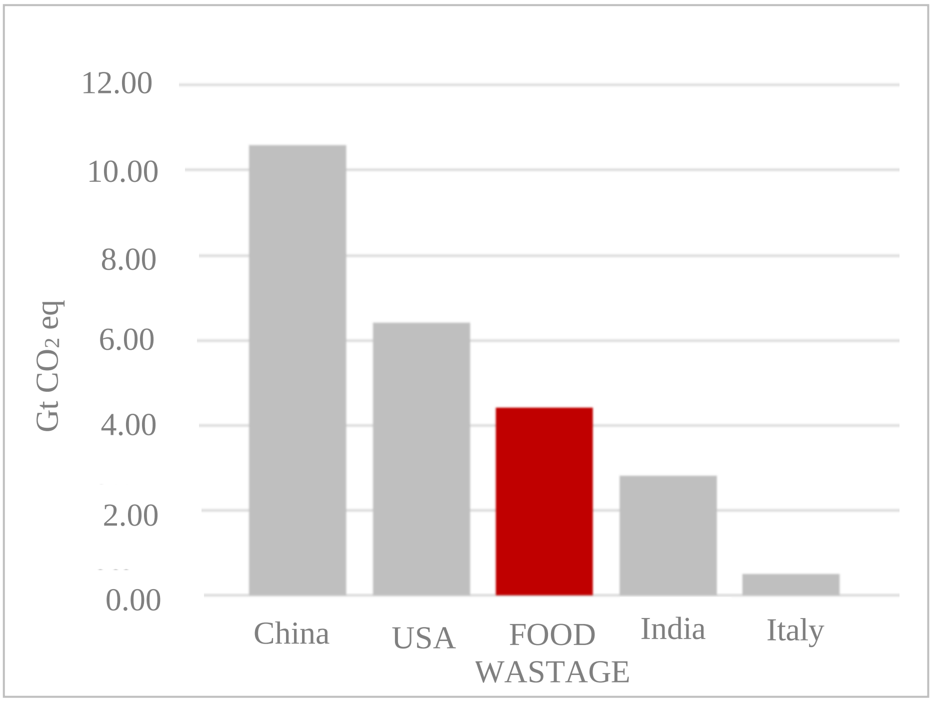

Figure 1: The GHGs emissions generated by food wastage worldwide (red column) compared to the highest GHG emitter countries. Adapted from: Food wastage footprint. Impacts on natural resources (FAO, 2013).

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[1] There are differences between the amount of waste generated in the FSC depending on the geographical location. For instance, food losses are higher in the upstream phases like agricultural production, post-harvest handling and storage, and transportation in developing countries. In comparison, losses and waste are higher at the production and consumption stage (e.g., retail, household, restaurant) in developed countries (FAO, 2011).

Wasting food does not damage only the environment. Indeed, the world population is expected to increase and with it the global demand for food. Thus, food wastage also represents a threat to food security (Bond et al., 2013). Furthermore, it is an economic loss for all stakeholders. For instance, the food losses only at the agricultural level are about USD 750 billion, the GDP of a country like Switzerland (FAO, 2013).

Luckily, governments and institutions recognized food wastage as a real issue that must be tackled at all levels of the FSC by all stakeholders, from farmers to consumers. New policies focus on food wastage and are gaining increasing attention at the European level. Some examples are the Farm to Fork Strategy (European Commission, 2020) and the Circular Economy Action Plan (European Commission, 2020), both included in the European Green Deal (European Commission, 2019). Furthermore, the United Nations drew up a set of Sustainable Development Goals (SDGs) to reach social, economic, and environmental sustainability. In particular, SDG 12 contains target 12.3 that aims at halving per capita food waste, reducing food losses along production and supply chains, reducing waste management costs, and maximizing the value from un-avoidable food waste by 2030 to establish responsible production and consumption patterns (UN, 2015).

What exactly is food wastage? Food wastage is the total amount of food diverted from human consumption. What is the difference between food loss and waste? Food losses generate during the initial stages of the FSC, from agricultural processes up to industrial transformations, including transportation, handling, and storage. Food waste, instead, refers to food wasted during the final stages of the FSC: retail and consumption (FAO, 2013).

Some experts consider by-products diverted away from the human food chain as food wastage (Stuart, 2009; Galanakis, 2020); others do not (Møller et al., 2014). By-products generate together with the marketable product, but they have a lower economic value. Thus, they often end up as waste. The author will refer to food waste independently if the waste generates at the beginning or end of the food supply chain. She will refer to food waste also when considering food by-products. Anyhow, selecting adequate terminology is not always straightforward (Caldeira et al., 2020).

1.2. The solutions

1.2.1. The circular economy

All the stakeholders can undertake several actions to tackle climate change and related issues caused by food production and waste. The most suggested practices would be implementing clean production methodologies (Galanakis, 2020), developing efficient production processes, and reducing food wastage at the source. Reducing food waste can be done by improving storage practices and the cold chain, educating farmers, employees, and consumers, through policymaking and redistributing food to people in need (Papargyropoulou et al., 2014).

However, reducing food waste is not always possible, especially at the industrial level. For example, the food industry generates by-products that are unavoidable (e.g., wheat bran from wheat milling) (Garcia-Garcia et al., 2017). Therefore, it is necessary to valorize such by-products to exploit the resources contained. The resources embedded in the waste could be kept in the biological cycle repeatedly, gaining more value at any round. This strategy is known as Industrial Ecology (Ayres et al., 1996). It contains solution frameworks such as the Circular Economy (CE) that aims at reaching a "zero waste" society (Mirabella et al., 2014). The final objective of the CE is to create intertwined economies where waste is used for new products and applications. Indeed, closed systems are the basis of the Industrial Symbiosis, in which the goal is to use wastes from one supply chain as an input for other supply chains (Chertow, 2007).

These approaches would help the food system become sustainable and resilient and help firms become more economically profitable. Indeed, the CE enables the reduction of resource and energy usage, waste generation, and GHG emissions. It enables energy-efficient systems, promote the use of renewable energy, and closes energy and material cycles (De Giovanni et al., 2019).

The circular economy is "an economic system based on business models that replace the "end-of-life" concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. Thus, it applies at the micro-level (products, companies, consumers), meso-level (eco-industrial parks), and macro-level (city, region, nation and beyond) to accomplish sustainable development[2] by creating environmental quality, economic prosperity, social equity, and benefits for both the current and the future generations" (Kirchherr et al., 2017).

In this thesis, the author focuses on the micro-level, in particular on the food industry.

The CE allows companies to move away from the obsolete linear approach "take-make-dispose" and switch to a circular system (cradle to cradle) in which economic welfare is maximized, together with environmental protection (ecology) and social benefits (equity) (MacArthur, 2013). Economy, ecology, and equity are the three pillars of sustainable development. Indeed, environmental sustainability is not enough.

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[2] “Sustainable Development: development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987).

The food produced must contribute to thriving local economies and provide social benefits, such as safe and healthy food (Galanakis, 2020). Also, using the available resources efficiently allows economic benefits.

1.2.2. From the Triple Bottom Line to the Triple Top Line

Elkington (Elkington, 1998) coined the term Triple Bottom Line (TBL), a framework that incorporates the three dimensions of sustainability in corporate performance. It is also known as the three P's framework: profit, people, and planet. However, it has always been considered as an accounting framework that aims at evaluating financial performances allowing CEOs, CFOs, or other corporates leaders to hit their profit targets and not their people and planet ones. It worked as a balancing act where corporates had to find trades-off between the three realms, always favouring the economy. Instead, Elkington proposed a triple helix for value creation that could have changed today’s system towards next-generation sustainable market solutions. Elkington himself is aware of the conceptual failure its system went through (Elkington, 2018). To overcome this conceptual misunderstanding, McDonough and Braungart (McDonough et al., 2002) proposed the Triple Top Line (TTL). The TTL aims at maximizing economic performance alongside social and environmental aspects without compromising (McDonough et al., 2002). They demonstrated that by maximizing the economy, ecology and equity, the company's profit increases, together with the people's well-being and planet preservation.

Thus, transitioning towards the circular economy means changing the perspective from the TBL to the TTL. Economy, ecology, and equity must be maximized and not balanced. Until this change in mindset does not occur, corporates will not approach the CE nor sustainable development. Therefore, it is essential to involve company directors, managers, and employees. Moreover, it is necessary to change systemically for effective actions (Meadows, 2008). Indeed, firms should expand the Triple Top Line to supply chain partners (e.g., farmers, suppliers, retailers) to reach a circular supply chain (Brown et al., 2018). If companies operate sustainably, also the suppliers must follow the same standards and offer “green” products to extend sustainable development to the whole food supply chain.

Finally, companies should team up to implement the Industrial Symbiosis, exchanging wastes and raw materials to create a clean and efficient industrial hub (Maranesi et al., 2020; Salomone et al., 2020). This aspect also aligns with the UN Sustainable Development Goal 17, "partnership for the goal" (UN, 2015).

1.2.3. Waste valorization

In the context of the CE, waste valorization plays a fundamental role (Teigiserova et al., 2020). Waste and by-products valorization has great potential within the industrial food sector. Food waste could be redistributed to needy people or used as animal feed. Moreover, since the food waste generated at the processing stage is highly homogeneous and concentrated it could be used to obtain high-added value products (Ong et al., 2017). It could be fermented to obtain bio-compounds or undergo extraction processes to obtain valuable molecules to produce food additives and pharmaceuticals (i.e., biorefinery concept) (Galanakis, 2020; Otles et al., 2018). Waste management solutions also include anaerobic digestion, composting, incineration with or without energy recovery, and landfilling (Valli, 2021).

Some valorization options are preferred since they provide higher environmental benefits (Papargyropoulou et al., 2014; Omolayo et al., 2021; Brancoli et al., 2020). For instance, re-utilizing food waste and by-products for human consumption, diverting the losses to animal feed or implementing the concept of bio-refinery and bio-industry are more efficient solutions than diverting waste to landfills or incineration.

1.2.4. Upcycling

Waste valorization that allows recovering valuable compounds for new high added value purposes (e.g., food ingredients from by-products) is also called upcycling or upgrading. Upcycling is a form of recycling. It consists in generating high-value products from waste material (Sung et al., 2015). “Upcycling (in addition to preventing food waste and loss) is a way to get the most value from the land, water, and agricultural inputs and effort that went into growing the food in the first place, that ensures that nutrients are kept in use at their highest value” (MacArthur, 2021).

McDonough and Braungart developed the concept at the beginning of the 21st century (McDonough et al., 2002; McDonough et al., 2013). Their books explain that it is not sufficient to find ways to valorize waste, but it is essential to design products that are circular and regenerative in their nature, and that can be upcycled with ease when they reach the end-of-life. Otherwise, the CE cannot be implemented. Thus, to upcycle, an eco-design approach must be adopted.

1.2.5. Eco-design

Eco-design, or circular design, or DfE - Design for the Environment is: "the systematic integration of environmental considerations into product and process design"

(ISO/TR14062:2002). Indeed, the environmental impact of a product can be levelled off only if the product is designed to be sustainable from raw materials sourcing to the product end-of-life (Zufia et al., 2008; Knight et al., 2009).

Raw materials sourcing consists in utilizing various ingredients (i.e., different from commodity food), low-impact and upcycled ingredients (e.g., plant-based and by-products), raw materials produced in a way that allows land and biodiversity to regenerate (i.e., crop rotation, organic farming). Moreover, a food product should be sustainable also at the end-of-life by designing the packaging in line with nature (e.g., biodegradable, recyclable, reusable) (Ellen MacArthur Foundation, 2021). Thus, an eco-designed product uses fewer and lower-impact resources, produces less waste (even if the goal should be reaching zero waste), eliminate emissions and pollution, and optimizes all stages of the production chain. At the same time, it ensures that the quality and safety of the product is preserved. Thus, it allows obtaining economic, social, and environmental benefits. Therefore, eco-design must be applied from the product conception to the end-of-life.

In this way, food companies could reach eco-innovation and adapt to changes that occur in society, increasing their competitive advantage, benefiting the environment, and favouring the people (Yannou-Le Bris et al., 2020).

1.2.6. Sustainability-oriented innovation

To implement the CE, thus upcycling waste and by-products into newly added value materials designed to be sustainable, companies must change their business model (Galanakis, 2020).

Indeed, the challenges our society is facing, like climate change, resources depletion, environmental degradation, and biodiversity loss, can become opportunities for food companies to engage in sustainability-oriented innovation (Joyce et al., 2016). Innovation is the instrument for food companies to stand out from competitors and fulfill consumer expectations while meeting sustainability goals (Menrad, 2004). Such innovations lead to conserve and improve natural, social, and financial resources. Therefore, by adopting innovative business strategies, the company can reverse today’s situation, shaping a sustainable food system and increasing its competitive advantage.

However, it is essential to engage company directors, employees, managers, and decision-makers to incorporate the TTL and the circular design into the corporate's goals. Indeed, top management attention and leadership are fundamental to implement CE strategies towards long-term growth and competitiveness (Meredith, 1998). They should promote and integrate innovative strategies internally and externally the company (Wooi et al., 2010).

This thesis focuses on actions to undertake internally to prioritize the sustainable organizational goals and motivate all employees to promote the new strategies.

2. The internship

The author did her thesis internship in Barilla - The Italian Food Company since 1877. Barilla is a multinational company with headquarter in Parma, Emilia-Romagna, a region in northern Italy. It is the leading pasta producer in Italy and worldwide, and it manufactures semolina pasta with the utmost attention to quality. Barilla also produces different kinds of ready sauces and offers almost 180 bakery products. Barilla has 28 production plants (14 in Italy and 14 abroad) and more than 8000 employees.

2.1. Barilla’s by-products

Barilla generates three valuable by-products during food processing. It produces wheat bran from wheat milling, pasta regrind during pasta making, and bread crust during crustless bread production. The author will not disclose the total amount of by-products the company produces for confidentiality reasons.

- Wheat bran is the edible outer layer of the wheat kernel, and it is obtained as a by-product during wheat milling when producing wheat flour. It is rich in fibres and antioxidant compounds (e.g., phenols like ferulic and vanillic acid) (Stevenson et al., 2012). Those components have health benefits acting as anti-carcinogenic compounds (Wang et al., 2008).
- Pasta regrind are the pasta scraps generated at the production plant during equipment cleaning and when the pasta shapes are changed. Luckily, it represents only 6% of the total waste in the pasta life cycle (the highest waste occurs at the consumer level) (Principato et al., 2019). Pasta regrind is an unavoidable by-product. Indeed, the pasta manufacturing process is already highly efficient, but considering Barilla's pasta production yearly, a considerable number of scraps is generated regardless (Tiziana De Micheli, personal comment).
- Barilla produces crustless bread since highly demanded by consumers. 40% of the bread is removed as crust even if the process is already highly efficient. The crust removed is still suitable for human consumption (Tiziana De Micheli, personal comment). This by-product/waste would be avoidable if consumers were aware of their food choices or if Barilla would stop producing it. Nevertheless, several food companies sell crustless bread, highlighting that its demand is rising (e.g., Puratos, Kingsmill). Therefore, from a brand positioning point of view, Barilla must be present in that market segment to keep consumers shares; thus, crustless bread production must continue (Tiziana De Micheli, personal comment).

2.2. Barilla’s by-products valorization

Barilla valorizes the by-products as animal feed (Tiziana De Micheli, personal comment). Such a solution aligns with the EU waste management recommendations regarding environmental protection strategies (EU 2018/851; Bos-Brouwers et al., 2020; Papargyropoulou et al., 2014). However, this option does not favour social and economic growth and it does not allow keeping by-products at their highest value to produce food for human consumption.

Indeed, animal feed's raw materials are sold at a low price or are not competitive with other available raw materials. Moreover, animal feed production does not provide Barilla with engaging storytelling; thus, it does not increase its reputation. Therefore, Barilla valorizes these by-products as animal feed without generating a profit, losing the chance to sensitize consumers about food waste, and without advertising the good practices the company does for the people and the planet.

Furthermore, meat production contributes to climate change (Ripple et al., 2014) and may lead to several health risks (Estruch et al., 2013). Therefore, many argue that meat consumption should drastically reduce (Farchi et al., 2017). Among them, also the Barilla Center for Food & Nutrition (BCFN, 2021) promotes the Mediterranean diet suggesting a plant-based diet with fewer meat servings per week (Ciati et al., 2012). Thus, the author thinks Barilla should look for other valorization alternatives to implement alongside animal feed production to reduce the amount of animal feed produced or the Barilla actions would not be in line with its statements. Alternative valorization options should lead to the TTL providing environmental, social, and economic sustainability. They should increase the reputation of the company and the engagement with consumers by taking care of the environment, save natural resources, implement the circular economy, and favour the local communities. At the same time, they should increase Barilla's profit.

At the beginning of her internship, the author started looking for ways to valorize Barilla’s by-products. Moreover, she attended induction sections with Barilla’s employees to understand Barilla’s valorization projects’ state of the art. She discovered that Barilla is aware of the available options since it collaborates with universities, organizations, other companies and bodies of the EU. However, each employee finds a different drawback in each project since they have diverse points of view. Furthermore, a company's vision about by-products valorization is also missing. Thus, upcycling projects have (almost) never be implemented.

Below, the author presents an overview of the valorization alternatives and the limits encountered.

2.2.1. Wheat bran

Barilla could collaborate with a company that develops single-use biodegradable and eatable tableware utilizing bioplastics like poly-lactic acid (PLA) with wheat bran as a filler (Biotrem, 2021). (For more information about PLA, the reader can consult the literature (Auras et al., 2011; Tueen et al., 2019)). Bio-tableware would replace single-use plastic materials banned by the European Commission (EU 2019/904). However, there are regulatory issues that hinder the use of wheat bran as plastic filler. In particular, DG SANTE, the Directorate General for health and food safety of the European Commission, has issued on May 28th 2021, a new communication that bans plastic objects containing vegetable fibres (e.g., wheat bran) intended to come into contact with food (Reg CE 10/2011). Moreover, this solution would not allow Barilla to utilize all the wheat bran available, leading to economic and logistic drawbacks.

Another option for wheat bran valorization is its use in cosmetics (e.g., body scrubs). An Italian company located in Parma developed a body scrub that utilizes wheat bran granules instead of microplastics (Cosmoproject, 2021). However, economic (section 3.1.1.3.1) and ethical issues made Barilla excluding the option. Indeed, is it fair to utilize food by-products still suitable for human consumption to produce a body scrub?

Wheat bran is a suitable material for implementing the bio-refinery concept (Cherubini et al., 2010). For instance, wheat bran fermentation produces lactic acid, succinic acid or ethanol. Moreover, proteins and essential amino acids, including γ-aminobutyric acid (GABA) and ferulic acid, could be obtained through extraction processes (Apprich et al., 2014). Besides, ferulic acid could be converted into vanillin to avoid vanillin production from fossil resources, a highly polluting process (Cavani et al., 2016; Kaur et al., 2013). Furthermore, arabinoxylans can be extracted from wheat bran to obtain nanomaterials (Sarker et al., 2020). Unfortunately, conventional extraction processes (e.g., solvent extraction) have substantial environmental burdens (Collotta et al., 2017). Therefore, experts are studying novel technologies such as Supercritical Fluid Extraction with CO2 (SCFE-CO2), High Hydrostatic Pressure Extraction (HHPE) and Ultrasound-Assisted Extraction (UAE) to replace conventional methods (Valli, 2021). However, their use is still at the laboratory scale, and the industrial trials require significant investments (Caldeira et al., 2020).

Finally, it is worth mentioning the project CartaCrusca developed by Barilla in collaboration with Favini, the worldwide leader in graphic specialities based on natural fibres (Favini, 2021). Barilla teamed up with Favini to produce a recycled paper made with 20% upcycled cellulose from wheat bran (Maranesi et al., 2020). It is the company's first and unique upcycle project (Giacomo Canali, personal comment).

2.2.2. Pasta regrind

Pasta regrind could be used to replace part of malted barley in beer production (Tiziana De Micheli, personal comment). High yield beer with good organoleptic properties has been obtained during an industrial trial carried out in an artisanal brewery. However, the project stopped because of ethical reasons related to the consumption of alcoholic beverages and the Covid-19 pandemic that hindered further in presence tastings.

Pasta regrind has also been investigated for producing bio-based drinking straws to replace plastic ones (Jonsson et al., 2021), thus reducing plastic waste. However, pasta straws do not provide the same drinking feelings as plastic straws, and there may be problems of consumers' acceptance. Moreover, some employees argued that pasta straws are not ethical (i.e., using food to produce a futile object), and a behaviour change is required instead (Barilla's employees, personal comment).

2.2.3. Bread crust

Bread crust could replace a fraction of malted barley in beer production (Brancoli et al., 2020). Some upcycled beers made by leftover bread are already on the market (Toast Ale, 2021; Baladin Briciola, 2021). However, there are ethical issues related to alcoholic beverage consumption.

Bread crust (and wheat bran) could be part of new pet food formulations (Castrica et al., 2018). Indeed, today's pet food production is a growing and profitable sector, and it contributes to climate change and related issues as human food production does (Schleicher et al., 2019). It requires raw materials production, storage, transport, processing, packaging, and it generates waste (Mosna et al., 2021). Therefore, sustainable pet food production should become a priority in the global sustainability agenda. Thus, the use of edible by-products to produce pet food has great potential. However, more research on pet nutrition is required (Swanson et al., 2013) and the selling price of bread crust to pet food producers should stay low as for animal feed.

Another opportunity would be to replace wheat flour with bread crust in product formulations. Barilla Research, Development and Quality managers (RD&Q) already developed a few recipes utilizing a different percentage of bread crust flour (Nadia Morbarigazzi, personal comment). However, the project would require a new line, thus further investments. Moreover, the market for upcycled food is still at its primordial stages in Italy and the EU, while it is already present in the US (Upcycled Food Association, 2021) (Barilla's employee, personal comment). Indeed, consumers will probably accept this solution for its ethical and environmental benefits (Yu et al., 2019). However, some experts believe consumers will not buy upcycled food since it would mean “eating waste” (Singh et al., 2019). Therefore, more marketing research is required (Barilla’s employee, personal comment).

Finally, solid-state fermentation of bread crust could be an option to obtain enzymes and proteins (Melikoglu et al., 2013; Verni et al., 2020). Nevertheless, many biotechnological processes are still at a low technological readiness level (TRL) (Zanaroli, 2021).

2.2.4. Multiple by-products

Barilla is investigating the feasibility to obtain bio-based and biodegradable plastic from its by-products. It is running pilot trials to verify the possibility to obtain valuable polyhydroxyalkanoates (PHAs) from wheat bran, pasta regrind and bread crust (Serafim et al., 2008; Koller et al., 2010; Tsang et al., 2019). PHAs are biopolymers obtained through microorganisms’ fermentation of sugars and lipids (Laura Mazzocchetti, 2020). Barilla is collaborating with startups at the global level to find the technology that best fits the company's needs. Moreover, Barilla supplies its raw materials to several EU projects funded under the Horizon2020 framework, the most extensive EU research and innovation program. Barilla is involved in the AgriMax (Valenturf et al., 2017; Gioia et al., 2019; AgriMax, 2021) and Usable Packaging projects (Usable Packaging, 2021). However, this up-and-coming solution is still under investigation.

2.2.5. Other companies' by-products

Barilla could collaborate with other companies (e.g., farmers, SMEs, corporates) and utilize their waste and by-products as raw materials. In this case, Barilla would not solve its "by-products problem", but it would implement the CE and the concept of Industrial Symbiosis partnering with other companies. Nevertheless, each actor in the food chain cannot only try to optimize their activities without considering the chain effects, and a food chain approach is instead needed (Sonesson et al., 2009).

Brewer’s spent grains (BSGs) could be raw materials for bakery products and pasta (Nocente et al., 2019; Ktenioudak et al., 2012). BSGs are the main by-product of beer brewing. They are rich in proteins and fibres, which make them suitable for human consumption. Their addition into food products would allow the achievement of nutritional benefits, thus adding nutritional claims to the food produced (Lynch et al., 2016). Furthermore, agri-food startups (Renewal Mill, 2021) are studying other by-products to upcycle. For instance, okara flour, the by-product of soymilk and tofu production (Li et al., 2012), could be added to bakery products to deliver healthy food rich in fibres (AR et al., 2020).

2.3. The problems with the solutions

The first month of the author's internship has been challenging. Indeed, Barilla's employees were already aware of all the upcycling solutions, but none seemed to be the perfect one. The valorization projects had much potential, but employees were confused about what upcycling is, what it means for Barilla, and which aspect should be prioritized when deciding. In short, Barilla had a problem because there were too many solutions and many conflicting criteria to evaluate the options.

To clarify employees' ideas and bring the topic to the managers' attention, the author collected the advantages and the disadvantages of the upcycling projects in a booklet. Writing the booklet allowed the author to place the light on the concept of upcycling. The company had previously introduced such a concept since it is willing to be a "good for the planet" corporate (as stated in its mission). However, managers and employees used to judge the upcycling projects mainly from the economic aspect, thus preventing many valorization options to become concrete.

Nevertheless, the implementation of sustainability is a long-term goal, and the benefits are not immediate. However, adopting new corporate strategies, shifting from the TBL to reaching the TTL, would bring profitability, competitiveness, social benefits, and positive environmental impacts (Maranesi et al., 2020).

2.4. The idea: the bread crust case study

The author and the tutor collected people from different departments, roles, (e.g., supply chain, marketing, strategy, agronomy, packaging, long term innovation, market insight specialists, product developers), office locations (e.g., Italy, Sweden) and brands (e.g., Wasa, Mulino Bianco, Gran Cereale) to create a multi-functional team gifted with different competencies, behaviours, and points of view. Around twenty colleagues voluntarily decided to join the Upcycling Team after the author first milestone. She explained that to end Barilla's by-products valorization struggle and to find the company’s common vision on upcycling, they needed to team up. Indeed, reaching the TTL is possible only if everyone works with the same aim for the company, the people, and the planet.

As a team, they first brainstormed the meaning of upcycling, trying to individuate its essential aspects. They shared a common vocabulary, creating a starting point for the company. Indeed, all sectors should coordinate before implementing the CE for effective and positive change.

To create the common ground to evaluate the valorization projects including all the sustainability criteria, the Team adapted an academic tool for multi-criteria decision making (MCDM) to the Barilla needs. They adopted the Analytic Hierarchy Process (AHP) (Saaty, 1988). Adopting the AHP allows screening the projects qualitatively, reducing the number of available options (section 3.1).

The author believes that AHP is difficult to explain but easy to apply. Thus, to help the reader understanding the process and providing him/her with the complete mathematical calculations that usually is taken for granted, she explains the AHP through a case study. In particular, she selected bread crust valorization. Indeed, it is the by-product that most urge upcycling because avoidable, edible, eatable, produced in larger quantities, and because its production leads to social debates (e.g., behavioural change, food security). For a complete definition of avoidable, edible, and eatable, the reader can consult Garcia-Garcia (Garcia-Garcia et al., 2017).

As seen in section 2.2.3, bread crust could upgrade to a food product, animal feed, or beer. Each of these alternatives has some advantages and disadvantages, but AHP aims to find the option that reduces the disadvantages to the minimum and enhances the advantages, not only economic.

Thus, this thesis attempts to screen the valorization options the market offers, basing the choice on the three most important aspects of sustainability: economy, ecology, and social equity. It does not pretend to provide a complete solution for Barilla, but it wants to act as an objective advisor and forerunner for future studies and decision projects.

Afterwards, to provide the company with a scientifically based result and justify the assumptions made while using AHP, Life Cycle Assessment (LCA) is carried out to evaluate the environmental impact of the best performing projects according to AHP (i.e., upcycled food, animal feed) (section 5). Indeed, not much information is available about upgrading food by-products into other food suitable for human consumption (section 4.1.). Therefore, the author compares the environmental impact of upcycled food and valorized feed, filling the knowledge gap due to the infancy of the processes (Sonesson, 2009).

The combination of MCDM and LCA is among the most used tools by researchers to assess the circular economy (Campos-Guzmán et al., 2019).

3. Methods, part I

3.1. Analytic Hierarchy Process

Thomas L. Saaty, Distinguished University Professor of Business Analytics and Operations, developed the AHP in the 70's. AHP is a multi-criteria decision-making method that helps decision-makers to face complex problems with multiple conflicting and subjective criteria (e.g., location or investment selection, projects ranking, etc.) (Saaty, 1987). It is advantageous and intuitive since it allows defining the problem systemically and judging elements in pairs. Indeed, psychologists believe it is easier and more accurate to express opinions on two alternatives (as in AHP) than on all the alternatives available (Ishizaka et al., 2011). That is why the Analytic Hierarchy Process is among the most used MCDM in business, research, marketing, and personal decision making (Taslicali et al., 2006). It translates psychological theories into math; thus, it helps to translate subjectivity into objectivity (Kiker et al., 2005). Three main steps characterize the AHP: problem definition (section 3.1.1.), pairwise comparison (3.1.2.), and problem recomposition (3.1.3.) (Saaty, 1987).

To run an AHP, Saaty developed Expert Choice, a software package used to make the calculations (Expert Choice, 1994). Even if it is user friendly and provides graphical results to facilitate the interpretation of the outcomes, buying a licence is expensive. Therefore, the author of this work developed an Excel spreadsheet (AHP calculations) that contains insights on the tool and provides examples for future users. Moreover, it allows inserting judgments through a guided set of questions and checks for inconsistency (section 2.1.2.3.). It probably lacks user-friendliness, but it guides Barilla decision-making process without financial investments. The spreadsheet allows to change the alternatives anytime there is the need to evaluate new upcycling projects.

3.1.1. First step: problem definition

The first step of AHP is the problem definition. The decision problem must be well structured. Indeed, the problem appears as a mind map that helps the decision-makers walking towards their decision. The mind map is a hierarchy composed of at least three levels: the goal, the criteria, and the alternatives. More levels (e.g., the sub-criteria) can be added depending on the problem to evaluate. The higher levels of the hierarchy (i.e., the goal and the criteria) are more general elements, whereas the lower ones (i.e., sub-criteria and alternatives) are more specific (Saaty, 1988).

The Barilla's Upcycling Team individuated a four levels hierarchy (Fig. 2). In the following sections, the four levels are explained in detail.

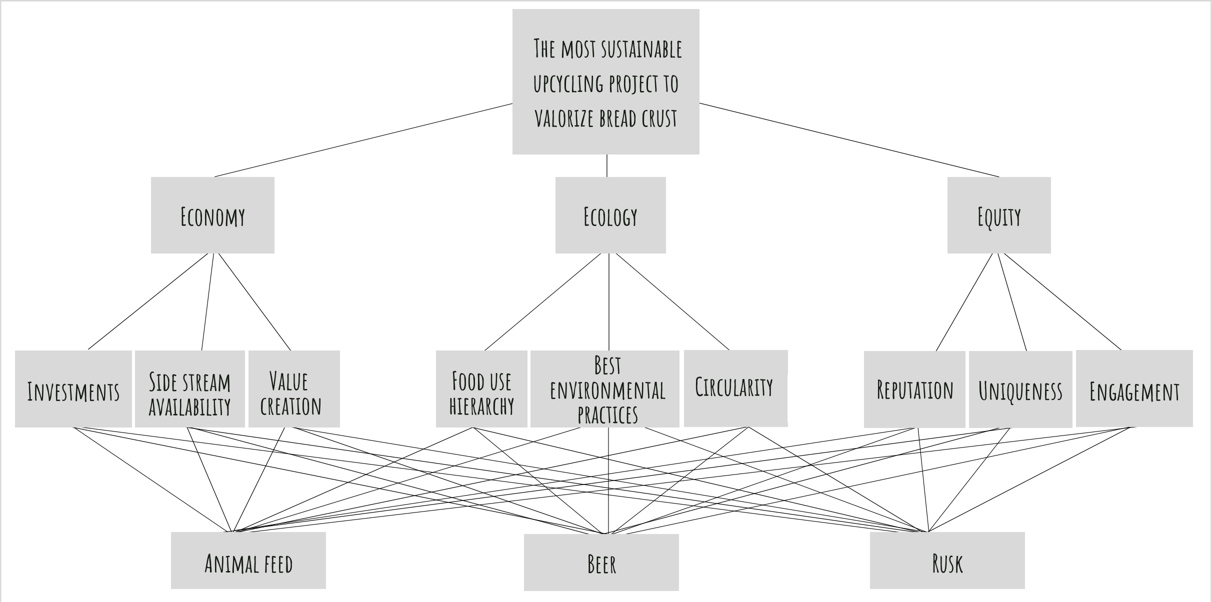


Figure 2: Decomposition of the bread crust valorization problem into a hierarchy.

3.1.1.1. The goal

The top-level of the hierarchy is the goal of the decision (Fig.2). The goal of the Barilla problem is to find the most sustainable upcycling project that allows Barilla to implement the circular economy and embrace sustainability in the context of bread crust valorization.

3.1.1.2. The criteria

The second hierarchy level is the level of the criteria that allows Barilla to reach the goal (Fig.2).

The author and her tutor facilitated the workshop that led the Team to select the Three E's framework (Ecology, Economy, Equity); also said the Three P's (Profit, Planet, People) or TBL. Indeed, now, the economic aspect has a higher weight in the corporate strategy. Hopefully, Barilla will approach the Triple Top Line soon, giving the same importance to the three criteria (McDonough et al., 2002) (Fig. 3).

The meaning of economy and ecology is relatively straightforward. With the criterion economy, the Team means the economic sustainability of the Barilla company. Instead, the criterion ecology underlines the benefits an upcycling project could bring to the environment.

Conversely, the criterion equity has a different meaning than the one contained in the Three E's framework. Usually, equity is the short version of Diversity, Equity and Inclusion (DEI) and focuses on people well-being (e.g., fair and equal wage, fair trade) (McDonough et al., 2002). Here, it focuses on the company well-being. Indeed, it measures the reputation the company could gain by implementing a valorization option. Nevertheless, the Team believes there is no need to consider DEI aspects in the decision problem since they are already an integral part of the company (Barilla's employees, personal comment). Moreover, focusing on society's perceived company's performance could push Barilla to care for people's well-being. Indeed, companies must look at society's needs to obtain a high reputation. Thus, the choice of this criterion offers the opportunity to integrate corporate goals with society's goals generating a win-win situation for both (El Akremi et al., 2018).

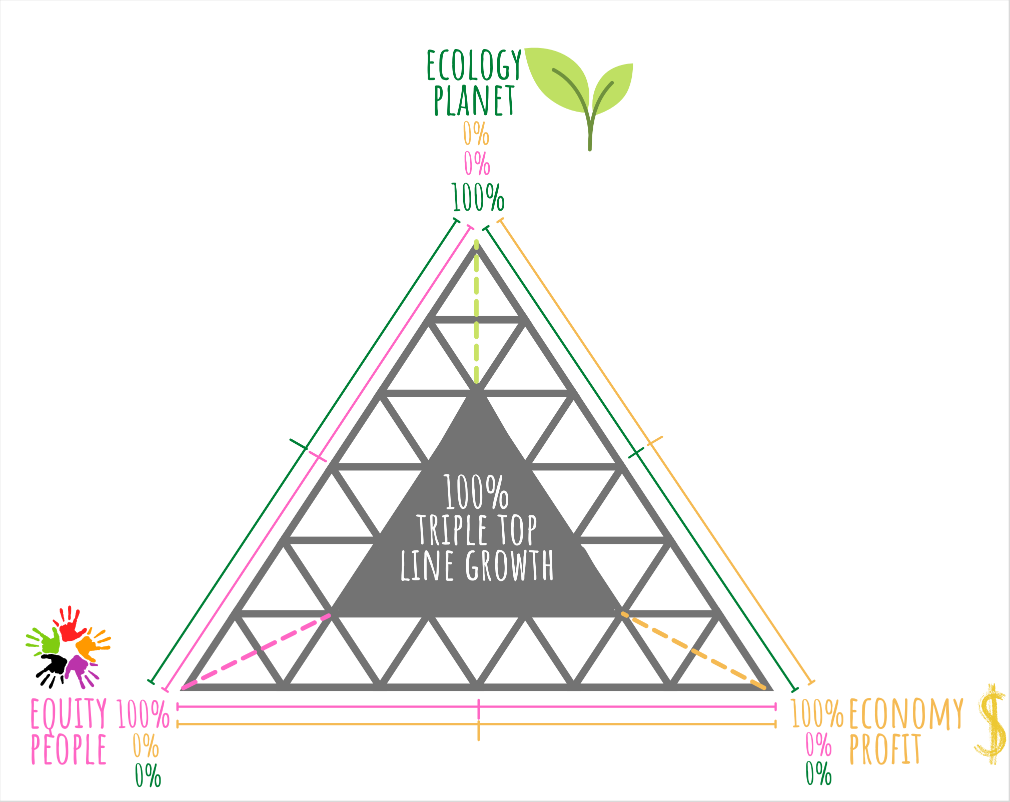


Figure 3: fractal triangle representing the Triple Top Line that aims at generating value in each category maximizing economy, ecology and social equity rather than balancing them. Adapted from William McDonough & Michael Braungart for green@work, 2003.

3.1.1.3. The sub-criteria

The sub-criteria constitute the third level of the hierarchy (Fig.2). The sub-criteria better describe, define, and explain the criteria of the level above.

The hierarchy the Team developed is said not complete (Saaty, 1990). It means that the sub-criteria selected do not refer to all the above criteria, but a cluster of sub-criteria refers to the economy criterion, another cluster to the ecology criterion, and another cluster to the equity one.

To define the sub-criteria, we divided the Upcycling Team into sub-groups. Sectors like supply chain, strategy, and product development met to define the economy's sub-criteria. They are:

- *Investment*
- *Availability match market demand*
- *Value creation*

Other sectors like marketing, people insight and strategy met to develop the equity sub-criteria, which are:

- *Reputation*
- *Engagement*
- *Uniqueness*

Finally, the health, safety, environment, and energy manager (HSE&E), agronomists, and packaging experts met to define the ecology sub-criteria. Open innovation was present in all sub-meetings. The ecology group decided to select the following sub-criteria:

- *Food use hierarchy*
- *Best environmental practices*
- *Circularity*

The following sections present a thorough sub-criteria description. Note that the sub-criteria are described and measured qualitatively by replying to a specific set of questions.

The reader may remember that some projects could be implemented by the Barilla company and marketed through a Barilla brand (e.g., snack production at the Barilla plant utilizing bread crust). Other projects could use third-party companies' by-products (e.g., BSGs, okara). Barilla could also decide to sell its by-products to a third-party company acting as a supplier without advertising the valorization (e.g., animal feed). Finally, it could create a collaboration with other companies (e.g., beer production and co-marketing brewery-Barilla) (section 2.2.). These four scenarios require considering the sub-criteria in a slightly different way depending on the situation.

3.1.1.3.1. Economy sub-criteria

Investments

- Does the project require a new line or a new capex to be implemented?

Decision makers should reply to this question when the valorization project occurs at the Barilla plants and already existing machineries are not sufficient to realize the project.

- Does Barilla need certifications to buy/utilize/sell other companies' or Barilla's by-products?
  The line between what it is considered waste no longer suitable for human consumption and what it is considered a by-product still suitable for human consumption is narrow (Directive 2008/98/EC). It is important to verify if the by-product requires certifications to be kept in the food chain. This evaluation may be expensive for the company.
- Does Barilla need to advertise the product?
  If the product is intended to be sold through a Barilla's brand, advertisement may be required.
- Does Barilla need to advertise the collaboration?
  Advertisement may be required to launch a collaboration between Barilla and other companies
- Does the project need costly pre-treatments to be implemented (e.g., dehydration)?
  Pre-treatments to transform/store the by-product may add an additional cost to the project implementation.
- Is the processing plant far from the by-product generation site?
  The transport costs must be considered.

Availability match market demand

Ideally, the amount of by-product available should be equal to the amount required by the valorization project.

- Is the by-product available not enough with respect to the one required by the valorization project?
  Barilla used to produce grated bread from scraps obtained during rusks production. However, the request for grated bread was much higher than the request for rusks. Thus, Barilla had to produce more rusks only to satisfy the market demand for grated bread. They soon understood that this way of proceeding was not economically sustainable. Indeed, more waste generation and more raw materials usage led to economic losses because of rusks overproduction.
- Is the by-product available in a high quantity with respect to the amount needed by the upcycling project?
  Barilla evaluated the possibility to sell wheat bran to a cosmetic company (Section 2.2.1). The company developed a face scrub made with bran pearls (instead of micro-plastic). However, the wheat bran produced at the Barilla's mills is higher than the cosmetic company could process. Barilla must know that selling its by-product to the company will not generate a considerable profit, and another solution for using the by-product may be still required (e.g.,

animal feed or others). From a short-term economic point of view, such a project is not well judged. However, in the long term, it could provide an economic advantage. Therefore, this case scenario is preferable to the one described above.

In short, a project that performs well under the sub-criterion *availability match market demand* utilize the same amount of by-product that generates.

Value creation

- Does the project generate revenues for Barilla?
- Does it represent a new business opportunity for the company?

  The above questions apply meanly when a project is implemented by a Barilla brand or by co-marketing processes.
- Is the by-product sold at a reasonable price?

  When the by-products are sold to third party companies, Barilla must make sure that the stream is sold at an equal or higher price with respect to animal feed (today's benchmark).
- Does Barilla have savings in waste disposal costs by valorizing the by-products?
- Is Barilla saving by reducing the need of virgin raw materials?
- Does Barilla have an acceptable/relevant/significant delivery margin?

3.1.1.3.2. Equity sub-criteria

Reputation

Reputation is the sum of impressions held by a company's stakeholders: employees, customers, investors, competitors, alumni, suppliers. It is the process and effect of transmitting a target image.

- Is the project ethical for consumers?
- Will the project be accepted/understood/approved/liked by the customers?
- Is the project in line with the company purpose? Is it ethical for the company?
- Could the project obtain a green claim?
- Social contribution: is the project doing something positive for the communities around the company (e.g., small producers, local communities, education)?
- Is the project solving a problem (environmental/social)?
- Is the product a high-quality product?
- If it is a food product, is it nutritious and healthy?

Uniqueness

- Would the competitiveness of Barilla increase?
- Is the project following a trend? Is it anyhow different from other projects?
- Is the project generating visibility for the company?
- Would customers buy Barilla's upcycled product?

Engagement

It measures the extent to which a consumer has a meaningful experience when exposed to commercial advertising, television contact, or other experiences.

- Can Barilla create a powerful storytelling?
- Is the project compelling, able to touch customers' senses?
- Can we establish new relations with new and old stakeholders?
- Does the project allow to co-create a co-marketing storytelling (e.g., cosmetic company and Barilla)?
- Can the reputation gained be propagated (word of mouth)?

3.1.1.3.3. Ecology sub-criteria

Food use hierarchy

Figure 4 shows the food use hierarchy adopted by Barilla's Upcycling Team. Projects at the top of the hierarchy are preferred to projects in the lower part. How the Team defined the hierarchy is explained in section 4.1.

Best environmental practices

- Does the project allow to obtain something that otherwise should have been obtained from non-renewable resources?

  We need renewable resources since they can play a key role in reuse, manufacturing, and recycling. They can create a low carbon economy where finite and fossil-based materials are replenished by sustainably sourced renewable materials (Ellen MacArthur foundation, 2021).
- Is the cycle of the project carried out within a limited number of kilometers?

  In 2017, 27% of total EU GHGs emissions were due to the transport sector (EU Transport GHG, 2017). Thus, reducing the km the by-products must travel before being upcycled would reduce the environmental impact of the valorization method.
- Does the project need energy consuming pre-treatments to be implemented?

Unless we rely on novel technologies, treatments such as dehydration are highly energy demanding (Galanakis, 2020).

- Is the project avoiding problem shifting?

  Sometimes, while solving a problem we generate another issue. Therefore, while implementing a new project it is important to adopt a holistic approach. Failure to think in a systemic way may lead to unintended consequences (Van den Bergh et al., 2015).

- Does the project reduce the need of plastic or does not need plastic at all?

  Plastic pollution is a global issue to tackle at all levels of the plastics supply chain. For a food company, it may be quite challenging to reduce the use of plastic. Indeed, it helps reducing food waste (Ozdemir et al., 2004). However, it is crucial to avoid overpackaging, and the use of toxic and non-recyclable materials (Borrelle et al., 2020).

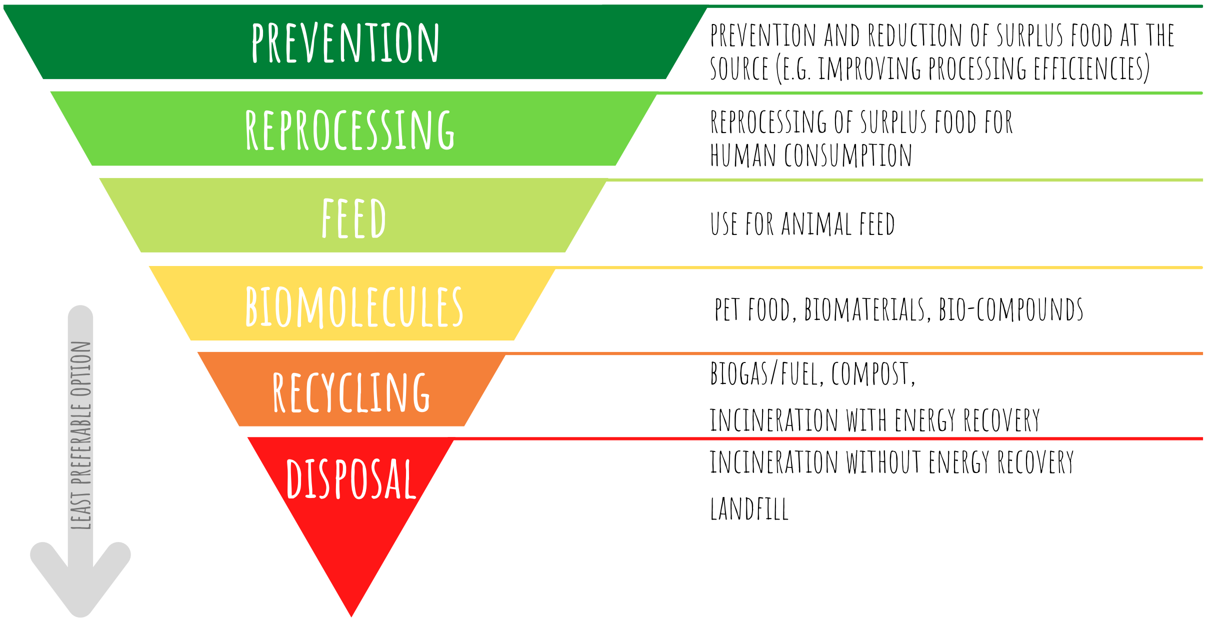


Figure 4: Barilla’s Upcycling Team Food use hierarchy. Inspired from “Assessment of Food Waste Prevention Actions” issued by the European Commission-Joint Research Center (JRC) (Caldeira et al., 2019), from the European project REFRESH (Metcalfe et al., 2017), and Sonesson and colleagues (Sonesson et al., 2009).

Circularity

- Does the project lead to additional waste generation while recovering resources from the by-product or while making a new product from it?
- How is the upcycled product being disposed of at its end-of-life? Is it recyclable, compostable, or reusable?

- Is the shelf life of the product long?
- Can Barilla use other by-products to make it, thus reducing even more the need of virgin material?
- Does it contain toxic substances that cannot be separated at the end-of-life stage?

Table 1 collects all the sub-criteria and their description.

3.1.1.4. Alternatives

The final level of the hierarchy is the level of the alternatives (Fig.2). The alternatives are the possible upcycling options subjected to the screening process. In the case study presented below, the team compared three possible bread crust valorization alternatives: animal feed, food production (i.e., rusk), and beer production. Energy production through incineration, composting, and anaerobic digestion is excluded because of the lower environmental benefits it provides (Papargyropoulou et al., 2014). Biotechnological processes like fermentation are excluded as well since they are not available at the industrial scale yet. The same applies to PHAs production.

3.1.2. Second step: pairwise comparison

The relative importance of criteria, sub-criteria, and alternatives is judged through pairwise comparison. Pairwise comparison is carried out considering actual measurements and preferences and feelings (Saaty, 1990). The ability of AHP to process judgements from exact measurements and feelings is a strength of the methodology. Indeed, it allows to judge physical events (e.g., what is tangible and objective) together with psychological events (e.g., what is intangible, subjective) (Saaty, 1990). Since using the AHP for the Upcycling Team will be a way to screen and prioritize alternatives before going deeper in their analysis and implementation, project ranking will be based essentially on feelings and preferences instead of direct measurements, which are time-consuming and costly for the company.

Pairwise comparison is used to establish relations between the elements of the decision problem. First, the decision-makers establish priorities for the level of the criteria by judging them in pairs for their relative importance with respect to the goal. After, priorities for the lower levels, the sub-criteria and the alternatives, are established.

Table 1: Sub-criteria description.

Criterion	Sub-criterion	Description
Economy	*Investments*	Does Barilla need certifications to buy/utilize/sell other companies' or Barilla's by-products? Does Barilla need to advertise the product? Does Barilla need to advertise the collaboration? Does the project need costly pre-treatments to be implemented (e.g., dehydration)? Is the processing plant far from the by-product generation site? Does the project require a new line or a new capex?
	Availability match market demand	Is the by-product available not enough with respect to the one needed by the valorization project? Is the by-product available in a high quantity with respect to the amount needed by the upcycling project?
	Value creation	Does the project generate revenues for Barilla? Does it represent a new business opportunity for the company? Is the by-product sold at a reasonable price? Does Barilla have savings in waste disposal costs by valorizing the by-products? Is Barilla saving by reducing the need of virgin raw materials? Does Barilla have an acceptable/relevant/significant delivery margin?
Equity	*Reputation*	Is the project ethical for consumers? Will the project be accepted/understood/approved/liked by the customers? Is the project in line with the company purpose? Is it ethical for the company? Could the project obtain a green claim? Social contribution: is the project doing something good for the communities around the company (e.g., small producers, local communities, education...)? Is the project solving a problem (environmental/social) or is it only a way to increase the company's profit? Is the product generated a high-quality product? If it is a food product, is it nutritious and healthy?
	Uniqueness	Would the competitiveness of Barilla increase? Is the project following a trend? Is it anyway different from other projects? Is the project generating visibility for the company? Would customers buy Barilla's upcycled product?
	Engagement	Can Barilla create a powerful storytelling? Is the project compelling, able to touch customers' senses? Can we establish new relations with new and old stakeholders? Does the project allow to co-create a co-marketing storytelling (e.g., cosmetic company and Barilla)? Can the reputation gained be propagated (word of mouth)?
Ecology	*Food use hierarchy*	Is the valorization option at the top of the pyramid?
	Best environmental practices	Does the project allow to obtain something that otherwise should have been obtained from non-renewable resources? Is the cycle of the project carried out within a limited number of kilometers (Km)? Does the project need energy consuming (pre)treatments to be implemented? Is the project avoiding problem shifting? Does the project reduce the need of plastic or does not need plastic at all?
	Circularity	Does the project lead to additional waste generation while recovering resources from the by-product or while making a new product from it? How is the upcycled product being disposed of at its end-of-life? Is it recyclable, compostable, or reusable? Is the shelf life of the product long? Can Barilla use other by-products to make it, thus reducing even more the need of virgin material? Does it contain toxic substances that cannot be separated at the end-of-life stage?

3.1.2.1. Scale of judgements

The fundamental scale of judgements, a linear scale from 1 to 9, is used to rank the levels of the hierarchy (Saaty, 1987) (Tab.2). The scale allows to translate verbal judgements into numbers. This is another strength of AHP. Indeed, decision makers and humans in general are more able to express themselves through verbal judgements. The scale has been validated for effectiveness by experts in different decision-making situations and through theoretical justifications (Beynon et al., 2002). However, the Barilla Upcycling Team decided to adopt a shorter linear scale of judgements. The scale goes from 1 to 5 (Tab.2).

Table 2: Fundamental scale of judgements developed by Saaty's and the Upcycling Team. Adapted from Saaty, 1987.

Intensity of importance on an absolute scale	**Saaty's definition**	**Saaty's explanation**	**Upcycling Team's definition**	**Upcycling Team's explanation**
1	Equal importance	Two activities contribute equally to the objective	Equal importance	Two activities contribute equally to the objective
2		Intermediate level of importance between the judgement above and below	Weak importance of one over another	Experience and judgment weakly favor one activity over another
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another	Moderate importance	Experience and judgment favor one activity over another
4		Intermediate level of importance between the judgement above and below	Strong importance	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another	Extreme importance	Experience and judgment extremely favor one activity over another
7	Very strong importance	An activity is strongly favoured and its dominance demonstrated in practice		
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation		
6,8	Intermediate values between the two adjacent judgements	When compromise is needed		
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*			

The Team argues that the aim of the application of the tool never relies on direct measurement; thus, they removed numbers 6,7,8 and 9 of Saaty's scale. Moreover, they consider it difficult individuating as many small nuances of judgment like when using the whole scale. In addition, they already utilize a 1 to 5 linear scale for sensory evaluations. Thus, they are used to a shorter scale, and the author believes that Barilla's managers and employees would accept and utilize the proposed tool if it is in line with the techniques already used by the company; therefore, she agrees with this choice.

2.1.2.2. Finding the criteria importance with respect to the goal

The judgements of the pairwise comparisons are inserted into matrices. The matrices are positive and reciprocal (Saaty, 1980). The number of judgements for a matrix of order *n* (the number of elements being compared) is *n*(*n*-1)/2 because it is reciprocal, and the diagonal elements are equal to unity (Matrix A). The author suggests reading Saaty's paper "Axiomatic foundation of the analytic hierarchy process" (Saaty, 1986) to understand the axioms governing the tool.

Matrix A: the criteria are pairwise compared with respect to the goal. The grey area highlights that the diagonal elements are equal to unity. The number of elements being compared is *n*=3 (i.e., economy, ecology, equity), and the number of judgements required to complete the matrix is 3 since equal to *n*(*n*-1)/2.

Goal	Economy	Ecology	Equity	Weight
Economy	1			
Ecology		1		
Equity			1	

Pairs of elements in the second hierarchy level are compared to the level above, the goal. Thus, the priority ranking (i.e., the relative priority of the criteria on a ratio scale) is established.
The decision-makers must reply to three questions since the number of judgements equals 3.
The questions to ask when comparing the elements in the hierarchy are of the following kind:

○ Is the *economy* criterion more important than *ecology* concerning the goal?
The economy criterion is considered essentially more important than ecology. Thus, the decision-makers attribute an intensity of 3 to the economy (Matrix A.a: light grey box).

Therefore, its reciprocal, 1/3, is automatically attributed to ecology and inserted in the transpose position (Matrix A.a: dark grey box).

Matrix A.a: The relative judgement of economy with respect to ecology is reported in the light grey box of the matrix. The relative judgement of ecology with respect to economy is reported in the dark green box.

Goal	Economy	Ecology	Equity	Weight
Economy	1	3		
Ecology	1/3	1		
Equity			1	

- ○ Is the *economy* criterion more important than *equity* concerning the goal?

  The economy is weakly more important than equity. Thus, the decision-makers attributed 2 to the economy and 1/2 to equity (Matrix A.b).

Matrix A.b: The relative judgement of economy with respect to equity is reported in the light grey box of the matrix. The relative judgement of equity with respect to economy is reported in the dark grey box.

Goal	Economy	Ecology	Equity	Weight
Economy	1	3	2	
Ecology	1/3	1		
Equity	1/2		1	

- ○ Is *equity* more important than *ecology* with respect to the goal?

  Equity is weakly more important than the ecology. Thus, the number 2 has been attributed to equity and 1/2 to ecology (Matrix A.c).

Matrix A.c: The relative judgement of equity with respect to ecology is reported in the dark grey box of the matrix. The relative judgement of ecology with respect to equity is reported in the light grey box.

Goal	Economy	Ecology	Equity	Weight
Economy	1	3	2	
Ecology	1/3	1	1/2	
Equity	1/2	2	1	

By answering these questions, the Team completed the first pairwise comparison. They must now derive each criterion's weights (or scale of priorities) (Saaty, 1987). They must solve for the principal eigenvector of the matrix and normalize the results to obtain the vector of priorities that points out the scores obtained by the criteria.
(economy, ecology, equity) = (0.540; 0.163; 0.297) (Matrix A.d).
For more insights about calculating the eigenvector, the author suggests consulting “The AHP: how to make a decision” (Saaty, 1990) or the Excel spreadsheet she created to do the calculations. In particular, the reader can visit the section named "Math" (AHP calculations).

Matrix A.d: The criteria local scale of priorities (in grey). (Economy, Ecology, Equity) = (0.540; 0.163; 0.297)

Goal	Economy	Ecology	Equity	Weight
Economy	1	3	2	0.540
Ecology	1/3	1	1/2	0.163
Equity	1/2	2	1	0.297

A visual representation of the criteria local scale is in Figure 5. The results are expressed in percentage for a clearer understanding. The economy criterion contributes 54% to the goal, while the ecology and equity criteria account for 16% and 30%, respectively.

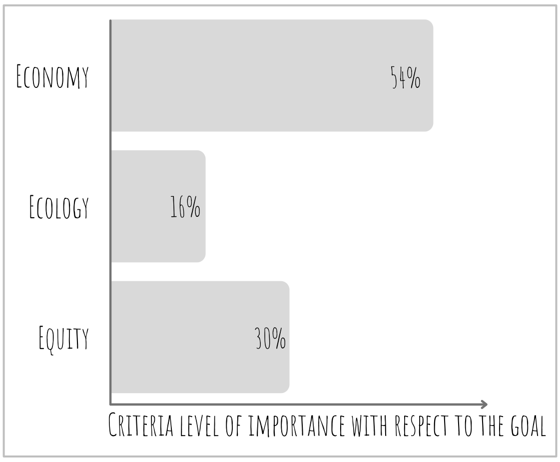


Figure 5: Criteria local scale expressed in percentage (the criteria local scale coincides with the criteria global scale since the goal weighs always unity (Saaty, 1990)).

When the TTL is fully adopted, the three criteria will have the same weight. However, Barilla is still transitioning towards the CE, and the corporate strategies are not entirely changed and adapted to the new business strategy. Therefore, the three criteria have different weights, and the economy criteria still prevails.

2.1.2.3. Consistency

The AHP decision-making methodology is equipped with a mechanism that allows controlling the consistency of the decision makers' judgements. A matrix is consistent when the transitivity rule holds for all elements. When the matrix of order *n* is consistent, the judgements have been consistent, and the principal eigenvalue has the value *n*. Conversely, when it is inconsistent, the principal eigenvalue exceeds *n* (Saaty, 1977).

Saaty proposed using the consistency ratio CR (Equation 1) to measure the consistency, which is the ratio between the consistency index CI (Equation 2) and the random index RI (Tab.3) (Saaty, 1977).

$$CR = CI/RI \qquad \text{(Eq.1)}$$

$$CI = \frac{\lambda \max - n}{n - 1} \qquad \text{(Eq.2)}$$

λ_{max} is the maximal eigenvalue and RI is the random index or the average CI of 500 randomly filled matrices (Tab. 3).

Table 3: Random indices from 500 randomly filled matrix by Saaty, 1977.

n	3	4	5	6	7	8	9	10
RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

To be an acceptable consistency, CR should not exceed 0.100. AHP tolerates 10% inconsistency since Saaty believes that some inconsistency is essential. Indeed, new findings able to change the priorities would not be admitted without admitting some inconsistency. In addition, as human beings, our judgements are, by definition, inconsistent (Saaty, 1977). However, the number of elements compared must not be too high (maximum 10); otherwise, their relative weight would be too small, and even a 1% inconsistency could distort the results. Thus, we must be sure that the weight of each element in the local scale weighs more than 10% on the total. For an in-depth mathematical explanation of how the consistency works for judgement matrices, the reader can consult Saaty's paper "AHP - what it is and how it is used" (Saaty, 1987).

The judgement matrix (matrix A.d) has λ_{max}=3.009, CI=0.005, and CR=0.008; thus, it is consistent, and the Team can proceed with the other judgements. Calculations for the CR have been made in the Excel spreadsheet that the reader finds in the supplement materials (AHP calculations).

3.1.2.4. Finding the sub-criteria importance with respect to the criteria they belong to

Pairwise comparison of the third hierarchy level, the sub-criteria, is carried out concerning the second level, the criteria. Three matrices, one for each criterion, are generated to obtain the sub-criteria importance scale. Each matrix has three elements to compare.

The pairwise comparison starts with the sub-criteria of the economy. The questions the Team must reply are:

- Are *investments* more important than *availability match market demand*?
- Is *availability match market demand* more important than *value creation*?
- Are *investments* more important than *value creation*?

In matrix B, the reader sees the judgements provided by Barilla's economy expert. The principal eigenvector has been calculated, and the results normalized. The consistency has been checked: CR= 0.016. A visual representation of the economy sub-criteria local scale is in Figure 6.

Matrix B: The economy sub-criteria scale of priorities. λ_{max}=3.018, CI=0.009, CR=0.016.

Economy	Investments	Availability match market demand	Value creation	Weight
Investments	1	4	2	0.558
Availability match market demand	1/4	1	1/3	0.122
Value creation	1/2	3	1	0.320

The Team pairwise compared the sub-criteria of equity. The local weights are presented in matrix C and the scores are presented in percentage (Fig.7). The consistency ratio calculated is 0.008, thus the matrix is consistent.

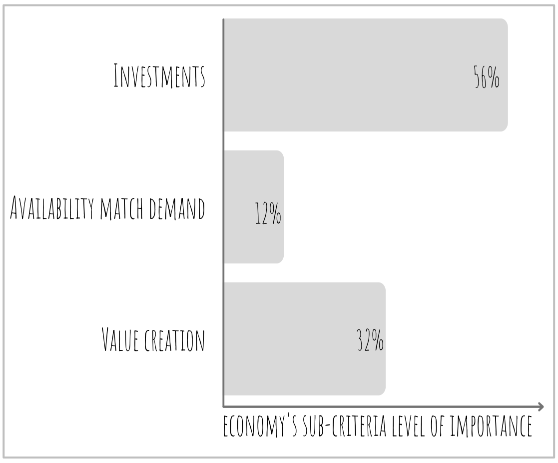


Figure 6: the economy sub-criteria local scale expressed in percentage.

Matrix C: the equity sub-criteria scale of priorities. λ_{max}=3.009, CI=0.005, CR=0.008.

Equity	Reputation	Uniqueness	Engagement	Weight
Reputation	1	3	2	0.540
Uniqueness	1/3	1	1/2	0.163
Engagement	1/2	2	1	0.297

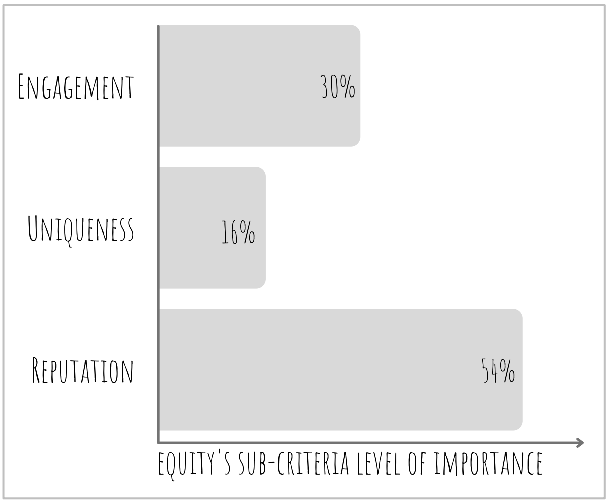


Figure 7: the equity sub-criteria local scale expressed in percentage

Finally, the Team discussed the judgements of the ecology sub-criteria (Matrix D; Fig.8)

- Is *food use hierarchy* more important than *best environmental practices*?
- Is *food use hierarchy* more important than *circularity*?

In both cases, the Team decided to attribute higher importance to the food use hierarchy criterion since it is a framework recognized by the EU.

- Is *best environmental practices* a more important criterion than *circularity*?
  The ecology experts believe the two criteria are equally important.
  The matrix is consistent since CR=0.000

Matrix D: the ecology sub-criteria scale of priorities. λ_{max}=3.000, CI=0.000, CR=0.000

Ecology	Food use hierarchy	Best environmental practices	Circularity	Weight
Food use hierarchy	1	2	2	0.500
Best environmental practices	1/2	1	1	0.250
Circularity	1/2	1	1	0.250

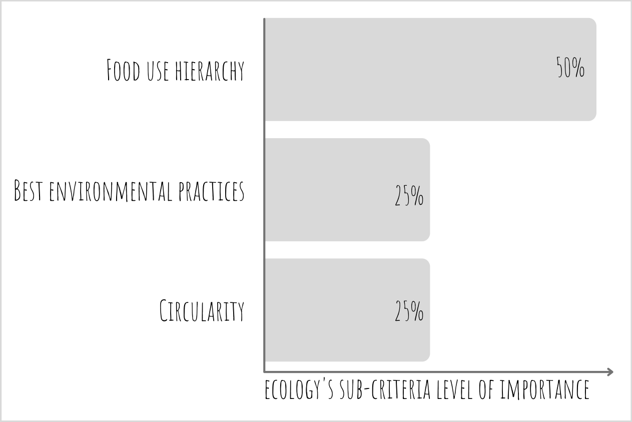


Figure 8: the ecology sub-criteria local scale expressed in percentage.

3.1.2.5. Finding the alternatives importance with respect to each sub-criterion

The pairwise comparison of the fourth level of the hierarchy, the alternatives, is carried out with respect to the sub-criteria, the third level of the hierarchy. In total, there are nine matrices, one for each sub-criterion. Each matrix compares three elements. Indeed, we compare animal feed, rusk and beer production. The alternatives' scale of priorities under the economy and equity criteria are not described in detail since they have been judged by marketing and financial experts. The local weights and the consistency ratio are presented in matrices E.a,b,c, and F.a,b,c.

The author would like the reader to notice that the way the questions are formulated can influence the judgements and thus the priorities. Therefore, it is essential to define the hierarchy's goal from the start and know if the levels fulfil that focus or are its consequence

(Saaty, 1987). Indeed, when the Team evaluates the alternatives with respect to the *investments* criterion, the questions they ask are of this kind:

- Does animal feed require *fewer* investments than rusk production?

High investments do not allow to reach the goal; actually, the best alternative should require only a few investments. Therefore, since we assumed that the hierarchy levels help to fulfil the goal, the Team had to adjust the question and demand which alternative requires *fewer* investments rather than which alternative requires *more* investments. With all the other (sub)criteria, the alternative that maximizes them gets a higher score; in this case, the option that minimizes the sub-criterion *investments* obtain the higher weight.

The complete questions the decision-makers replied to are contained in the Excel spreadsheet (AHP calculations).

Matrix E: Alternatives local scale with respect to the sub-criteria of economy.

a) Alternatives local scale with respect to investments. λ_{max}=3.018, CI=0.009, CR=0.016.

Investments	Beer	Feed	Rusk	Weight	%
Beer	1	1/3	2	0.238	24
Feed	3	1	4	0.625	62
Rusk	1/2	1/4	1	0.136	14

b) Alternatives local scale with respect to value creation. λ_{max}=3.074, CI=0.037, CR=0.063.

Value creation	Beer	Feed	Rusk	Weight	%
Beer	1	3	1/3	0.268	27
Feed	1/3	1	1/4	0.117	12
Rusk	3	4	1	0.614	61

c) Alternatives local scale with respect to availability match market demand. λ_{max}=3.000, CI=0.000, CR=0.000

Availability match market demand	Beer	Feed	Rusk	Weight	%
Beer	1	1/2	2	0.286	29
Feed	2	1	4	0.571	57
Rusk	1/2	1/4	1	0.143	14

Matrix F: Alternatives local scale with respect to the sub-criteria of equity.

a) Alternatives local scale with respect to engagement. λ_{max}=3.039, CI=0.019, CR=0.033

Engagement	Beer	Feed	Rusk	Weigh	%
Beer	1	3	1/3	0.258	26
Feed	1/3	1	1/5	0.105	10
Rusk	3	5	1	0.637	64

b) Alternatives local scale with respect to uniqueness. λ_{max}=3.004, CI=0.002, CR=0.033

Uniqueness	Beer	Feed	Rusk	Weight	%
Beer	1	3	1/2	0.309	31
Feed	1/3	1	1/5	0.109	11
Rusk	2	5	1	0.582	58

c) Alternatives local scale with respect to reputation. λ_{max}=3.054, CI=0.027, CR=0.046.

Reputation	Beer	Feed	Rusk	Weight	%
Beer	1	1/2	1/4	0.131	13
Feed	2	1	1/4	0.208	21
Rusk	4	4	1	0.661	66

Matrices G.a,b,c contains the judgements concerning the sub-criteria of ecology.

- Does *rusk* rank higher in the *food use hierarchy* with respect to *animal feed*?

  Re-processing of food waste into food products has been placed at the top of the Upcycling Team’s food use hierarchy. Regardless, using by-products as animal feed is considered an environmentally friendly option ranking slightly lower than redistribution (Section 3.1.1.3.3.). Thus, rusk gains 2 and animal feed 1/2.

- Does *rusk* rank higher in the *food use hierarchy* compared to *beer*?

  Beverage production is considered as food production (Barilla’s employees, personal comment). Thus, the decision-makers attributed 1 to both.

- Does *beer* rank higher in the *food use hierarchy* compared to *animal feed*?

  Since rusk is weakly more preferable than animal feed, and rusk and beer production rank equally, to be consistent, beer should rank weakly more than animal feed.

- Does *rusk* production follow more *best environmental practices* compared to *animal feed*?

The Team assumed that rusk production requires slightly more energy than animal feed mainly because of treatments required to ensure food safety. Moreover, the Team assumed that the production of the rusk occurs at the Barilla plant, and they considered that animal feed is produced in the same industrial area where Barilla is located. Thus, transport is not required in both cases. Finally, they consider that a food product requires more packaging than animal feed (e.g., single portions). Therefore, animal feed gains 2.

- Does *rusk* production follow more *best environmental practices* than *beer*?
  The Upcycling Team believes that they perform equally also in this sub-criterion. Indeed, to produce beer, the bread must be transported to the beer production site, whereas rusk would be produced where the bread crust is obtained. However, rusk requires plastic packaging (which is considered a drawback by the Barilla company), while beer relies on aluminium or glass packaging which is considered better than plastic by the company (and especially consumers) (Barilla's employee, personal comment).
- Does *beer* production follow more *best environmental practices* compared to *animal feed*?
  For coherence, animal feed gains a 2.

- Does *rusk* production allow to implement *circularity* more than *animal feed*?
- Does *beer* production allow to implement *circularity* more than *animal feed*?
- Does beer production allow to implement *circularity* more than *rusk* production?
  The Team believes circularity is accomplished equally in all three alternatives.

Matrix G: Alternatives local scale with respect to the sub-criteria of ecology.

a) Alternatives local scale with respect to food use hierarchy. λ_{max}=3.000, CI=0.000, CR=0.000

Food waste hierarchy	Beer	Feed	Rusk	Weight	%
Beer	1	2	1	0.400	40
Feed	1/2	1	1/2	0.200	20
Rusk	1	2	1	0.400	40

b) Alternatives local scale with respect to best environmental practices. λ_{max}=3.000, CI=0.000, CR=0.000

Best environmental practices	Beer	Feed	Rusk	Weight	%
Beer	1	1/2	1	0.250	25
Feed	2	1	2	0.500	50
Rusk	1	1/2	1	0.250	25

c) Alternatives local scale with respect to circularity. λ_{max}=3.000, CI=0.000, CR=0.000.

Circularity	Beer	Feed	Rusk	Weight	%
Beer	1	1	1	0.333	33%
Feed	1	1	1	0.333	33%
Rusk	1	1	1	0.333	33%

3.1.3. Third step of AHP: Recomposition

Problem recomposition allows to establish the global priorities of the alternatives (Saaty, 1990). We lay out in a matrix: the local priorities of the alternatives with respect to each sub-criterion, the local priorities of each sub-criterion with respect to the criteria, and the priority of each criterion with respect to the goal. Afterwards, we multiply the vectors' columns to obtain the alternatives scale with respect to each weighted criterion (Matrix H).

Matrix H: alternatives global scale with respect to economy, equity, ecology.

Alternative	**Investments (Matrix E.a)**	**Value creation (Matrix E.b)**	**Availability match demand (Matrix E.c)**	X	**Sub-criteria local scale (Matrix B)**	X	**Criteria local scale (Matrix A)**	=	**Alternatives scale with respect to economy**
Beer	0.238	0.268	0.286		0.558		0.540		0.137
Feed	0.625	0.117	0.571		0.320				0.246
Rusk	0.136	0.614	0.143		0.122				0.157
Alternatives	**Engagement (Matrix F.a)**	**Uniqueness (Matrix F.b)**	**Reputation (Matrix F.c)**	X	**Sub-criteria local scale (Matrix C)**	X	**Criteria local scale (Matrix A)**	=	**Alternatives scale with respect to equity**
Beer	0.258	0.309	0.131		0.297		0.297		0.059
Feed	0.105	0.109	0.208		0.163				0.048
Rusk	0.637	0.582	0.661		0.540				0.190
Alternatives	**Food use hierarchy (Matrix G.a)**	**Best environmental practices (Matrix G.b)**	**Circularity (Matrix G.c)**	X	**Sub-criteria local scale (Matrix D)**	X	**Criteria local scale Matrix A**	=	**Alternatives scale with respect to ecology**
Beer	0.400	0.250	0.333		0.500		0.163		0.057
Feed	0.200	0.500	0.333		0.250				0.050
Rusk	0.400	0.250	0.333		0.250				0.057

Then, for each alternative, we add the scores they obtained in each criterion to obtain the desired vector of the alternatives (Matrix I). Rusk is the alternative with the largest priority, 40%. It is followed by animal feed (34%) and, last, by beer production (25%). Figure 9 presents a visual representation of the scores in percentage.

For an insightful description of the calculations, the reader can consult Saaty's examples (Saaty, 1990) and the Excel file edited by the author (AHP calculations).

Matrix I: Alternatives global weight.

Alternative	**Alternatives scale with respect to economy**		**Alternatives scale with respect to equity**		**Alternatives scale with respect to ecology**		**Alternatives global weight**
Beer	0.137	+	0.059	+	0.057	=	**0.252**
Feed	0.246	+	0.048	+	0.050	=	**0.344**
Rusk	0.157	+	0.190	+	0.057	=	**0.403**

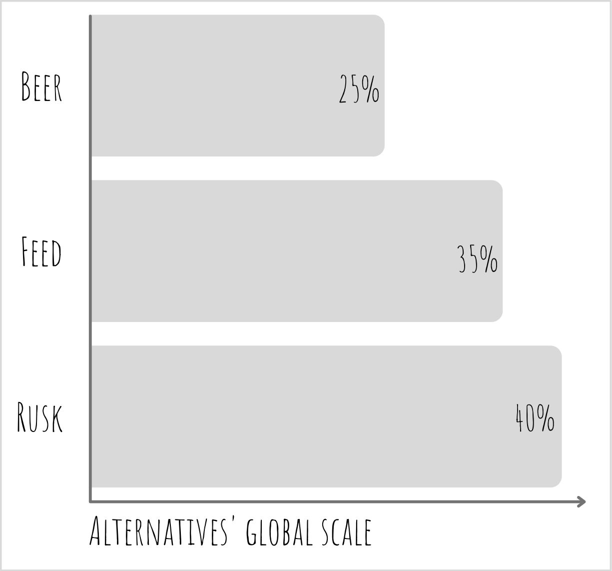


Figure 9: alternatives' global scale in percentage. Data adapted from Matrix I. Rusk is the option better performing in all aspects of sustainability.

3.1.4. Sensitivity analysis

To test the stability of the priority ranking, a sensitivity analysis must be carried out (Chang et al., 2007). Indeed, the absolute priorities of the alternatives are highly dependent on the weights attached to the main criteria. Small changes in the relative weights can cause significant changes in the final ranking. Since these weights are usually based on highly subjective judgments, the stability of the ranking under varying criteria weights must be tested. For this purpose, sensitivity analysis can be performed based on scenarios that reflect alternative future developments or different views on the relative importance of the criteria. By increasing or decreasing the weight of individual criteria, the resulting priorities and ranking of the alternatives can be observed. It is recommended to carefully reviewing the judgements if the ranking is highly sensitive to small changes in the criteria weights. For this purpose, the weights of the criteria have been separately altered to check the stability of the result obtained. The different weights have been changed in the Excel spreadsheet (AHP calculations) that provided the new results.

- Increase the economy weight by 17%.

  Increasing the economy weight leads to having animal feed as the preferred option, almost on par with rusk (beer; feed; rusk) = (0.254; 0.387; 0.359).
- Increase equity weight by 37%.

  Increasing the equity weight by 37% leads to having rusk as the preferred option.
  (beer; feed; rusk) = (0.225; 0.243; 0.532).
- Increase ecology weight by 55%.

  It leads to having rusk as the best option, even if both animal feed and beer are slightly less favoured. (beer; feed; rusk) = (0.313; 0.318; 0.369)
- Reaching the Triple Top Line

  The three criteria have the same weight. Rusk results the alternative with the highest rank.
  (beer; feed; rusk) = (0.266; 0.309; 0.426)

4. Results and discussion, part I

4.1. Ecology sub-criteria

Food use hierarchy

In this section it is explained how the Barilla's food use hierarchy (Fig.4) has been obtained.

The European policy introduced the waste hierarchy in the 1970s (European Parliament Council, 1975; European Commission, 1977; European Parliament Council, 1989), and it became the primary framework for waste management options. The updated European Waste Framework Directive (2008/98/EC) contains, in Article 4, a new hierarchy that sets out five tiers for dealing with waste in a preferred order. The framework focuses on reducing, reusing, recycling, and recovering (Fig.10).

Life cycle assessment allowed the European Commission to prioritize the options. Indeed, the hierarchy only refers to environmental aspects, and it does not consider social or economic issues (European Parliament Council, 2008).

Some studies adapted the waste hierarchy to food waste (Papargyropoulou et al., 2014; WRAP, 2011; REFRESH, 2016; EPA, 2021). The top part of the hierarchy represents the most suggested options and focuses on prevention actions, redistribution, and reusing food into value-added products (upcycling). It is followed by recycling (e.g., anaerobic digestion and composting); incineration and landfilling are in the bottom part and represent waste disposal alternatives to avoid (Fig.11).

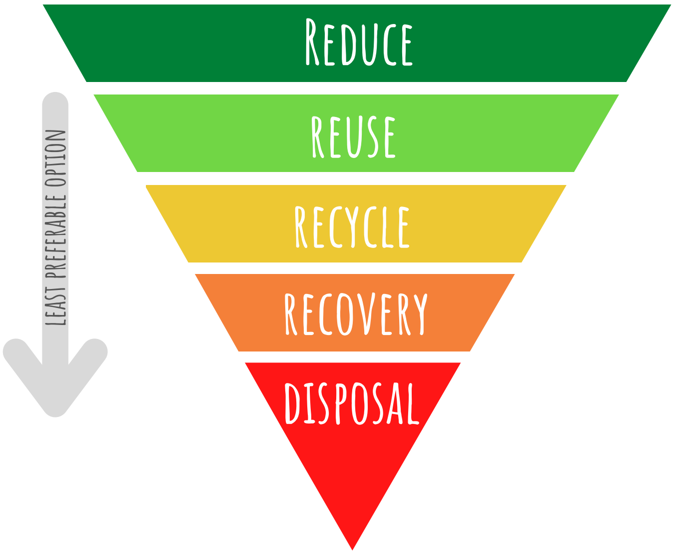


Figure 10: Waste hierarchy. Adapted from the European Parliament Council (European Parliament Council, 2008).

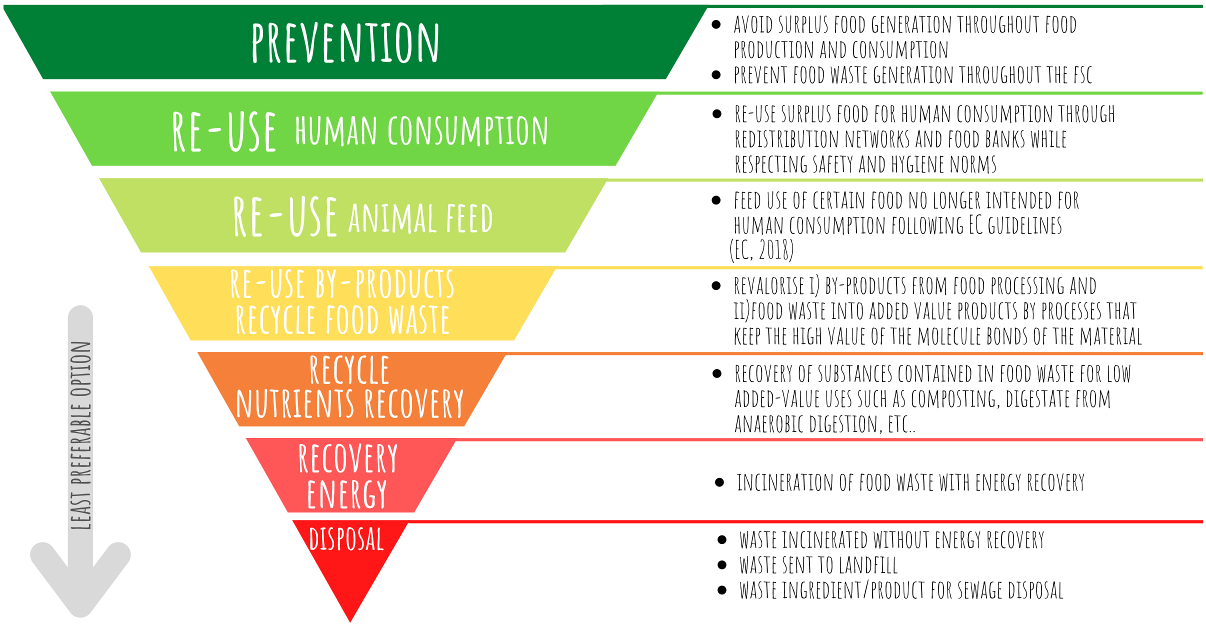


Figure 11: Hierarchy for prioritization of food surplus, by-products, and food waste prevention strategies. Taken from “Brief on food waste in the European Union” (European Commission Joint Research Centre, 2020).

The Upcycling Team decided to use the food hierarchy as a criterion because it has a scientific foundation (i.e., LCA), and eventual discrepancies with the reality may be negligible. However, the reader must bear in mind that only a site-specific and accurate LCA study can confirm that the valorization method selected is the one that allows obtaining the highest environmental benefits (2008/98/EC).

Anyhow, Barilla already excluded waste management options such as composting, anaerobic digestion, incineration, and landfilling from its array of alternatives since they are the least preferable ones. (REFRESH, 2016). Therefore, following the hierarchy and prioritizing its upper part should not lead to severe environmental impacts but eventually to slightly fewer benefits.

The reader is invited to notice that the food waste hierarchy of figure 11 places "reuse for human consumption" as the best option after "prevention". However, it states that such food is distributed to needy people through networks and food banks. It does not mention to reprocess food waste or by-products to make other food products. Nevertheless, it is a piece of necessary knowledge for Barilla decision problem.

Therefore, upgrading food by-products/waste to make other food products is among the best or the worst options? Is it considered as redistribution, reuse or recycling? In which position of Barilla’s food use hierarchy should be present? Unfortunately, the literature lacks studies of this kind.

Only the "Assessment of Food Waste Prevention Actions" issued by the European Commission-Joint Research Center (JRC) states that within the food waste prevention actions, there is the "value-added processing" option that suggests processing surplus food or by-products into other food products (Caldeira et al., 2019). Also, the European Horizon2020 funded project REFRESH considers reprocessing by-products for human consumption a food waste prevention strategy (Metcalfe et al., 2017). However, its priority level with respect to other waste prevention strategies is not clear to the author of this study.

Sonesson and colleagues (Sonesson et al., 2009), instead, compared the use of BSGs for food and animal feed production through LCA. They obtained that producing an upcycled food product has a lower global warming potential (GWP) than producing feed when considering the avoided production of a standard snack.

Therefore, the Upcycling Team's food use hierarchy (Fig.4) has been based on the literature results cited above. However, the author of this work justified the assumptions made when defining the food use hierarchy by carrying out a LCA (Section 5).

Best environmental practices

The reader should notice that when the Team evaluates the alternatives under the criterion *best environmental practices*, the judgements are highly qualitative and made depending on personal knowledge, beliefs, or information gathered in the literature. Indeed, LCA, the scientific tool usually adopted to quantitatively evaluate the environmental impact of products and services, requires human resources, time, and it is financially expensive. Therefore, the Barilla Upcycling Team decided to avoid judging the alternatives using LCA in the screening phase (while applying the AHP), and they agreed to use a qualitative criterion.

Circularity

Circularity is estimated qualitatively as well. Indeed, calculating circularity quantitatively is difficult. Unfortunately, there is not a unified measurement method accepted by experts yet (Morone et al., 2020). Many (Corona et al., 2019; Lokesh et al., 2020) believe LCA is a potential framework for measuring circularity. Others think it has some limitations (Reap et al., 2008).

Among the first circular economy standards, there was the BS 8001:2017, followed by the Circular Economy Action Plan (European Commission, 2020). Lately, organizations and private companies are also contributing to measure the circularity of products, processes, and companies. While offering a practical approach, they include societal and economic evaluation into environmental ones. The CirculAbility (Enel, 2020) and the Circulitycs (Ellen MacArthur

Foundation, 2019) tools seem to gain recognition among experts. However, they are not fully recognized yet. For these reasons, the Team believes that a qualitative approach to measuring circularity is sufficient until new and more complete tools develop.

4.2. Equity sub-criteria

The author disagrees with the Upcycling Team in the choice of the equity sub-criteria. Indeed, she believes that *uniqueness* and *engagement* should be clustered together with the economy's sub-criteria since they are highly related to the company's profit. Instead, she thinks that the sub-criterion *reputation* fits the equity area. Anyhow, *ethics* would have been a better name for the criterion instead of equity to avoid misunderstanding.

Barilla's equity sub-criteria point out that the TTL is not reached yet. Indeed, transitioning from the TBL to the TTL requires time and changes in mindset, and it cannot occur perfectly and immediately. Nevertheless, bringing those topics to the attention of decision-makers can only speed up the process.

4.3. Sub-criteria

The sub-criteria are not SMART (Doran, 1981). They are not Specific, Measurable, Time-bound, and their evaluation is subjective and qualitative. Thus, the result obtained with AHP should not be considered an absolute result and must always be judged with criticism.

Anyhow, the methodology helped evaluate every alternative under the same set of eyes, and most importantly, it allowed to raise awareness among managers and employees about circular economy thinking. Indeed, to transition towards the circular economy, a systemic change within the whole company is necessary, and the adoption of the new business strategies must involve all departments. Thus, thanks to the use of AHP, the Team brought people together, managed to brainstorm the problem, looked for solutions and their limitations, and introduced the circular economy concept.

4.4. Upcycled rusk

Applying the AHP to Barilla's by-product valorization problem allows the Team to reason about the different alternatives. They obtain that rusk is the favourite option (Fig.9).

Animal feed would be the alternative to performing better from the economic point of view (Fig.12). Indeed, it does not require high investments, and for this reason, it gained a high rank in the investments sub-criterion (22.5%) (Fig.13.b) with respect to its overall weight (35%) (Fig. 9). However, rusk performs well in the economy criterion and better than animal feed and beer in the equity one (Fig.12). Figure 13.c shows that the sub-criteria of equity contribute to half of the rusk alternative weight. Finally, all three alternatives perform equally under the criterion ecology (Fig.12). Thus, rusk results in the alternative able to provide equity advantages, but also economic and environmental.

The priority ranking is characterized by high stability, considering the results obtained in the sensitivity analysis simulations. Indeed, rusks result in the preferred alternative in (almost) all cases (Section 3.1.4).

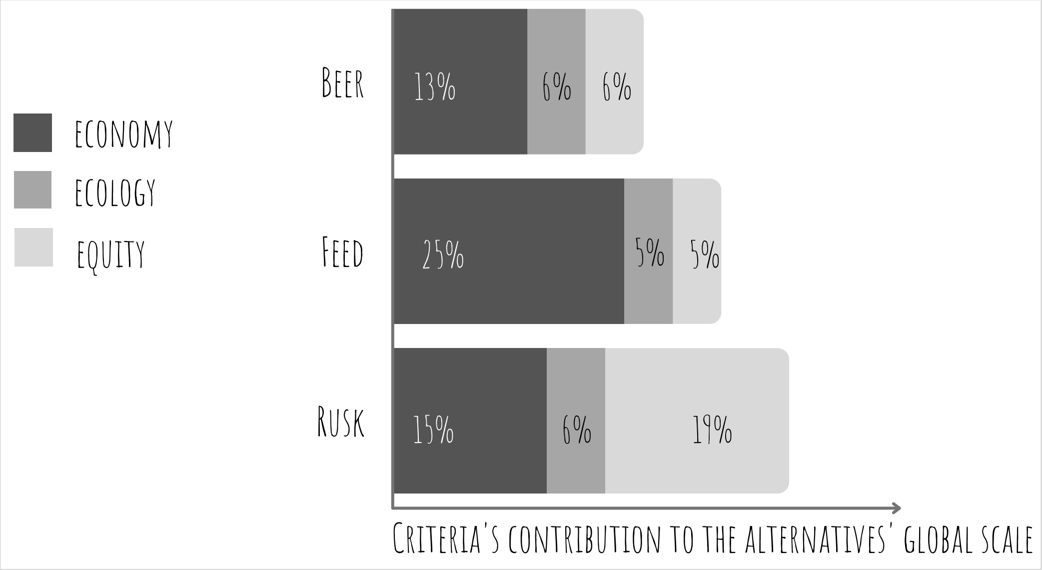


Figure 12: criteria's contribution to the alternatives global scale. Data taken from Matrix H.a,b,c. The figure shows that the economy criterion contributes for the 13%, ecology for the 6%, and equity for the 6% to the overall *beer* weight, which is 0.252 with respect to the goal (or 25%) (recall Fig.11). In *animal feed*, which has overall importance of 35% with respect to the goal (0.344), economy matters for the 25%, ecology for the 5%, and equity for the 5%. Finally, *rusk* weighs 40% in relation to the goal (0.403). Such 40% is provided by 15% of economic aspects, 6% of ecological aspects, and 19% of equity aspects.

4.5. Limitation and strengths

Some may argue that diminishing the integers in the scale of judgements (Section 3.1.2.1.) is a limitation of the method. However, adopting a linear scale should change nothing. Instead, what would make some changes to the AHP global priorities scale and consistency check would occur by adopting other numerical scales (e.g., square root scale, geometrical scale…) (Ishizaka et al., 2011). Therefore, the reduced scale is acceptable, but it is crucial to define the meaning of the scale used to allow all decision-makers to judge the elements correctly.

Another limitation to the process could be the number of decision-makers. Group decision-making can strengthen the AHP methodology since it avoids bias that may be present when a single person makes the judgements (Ishizaka et al., 2011).

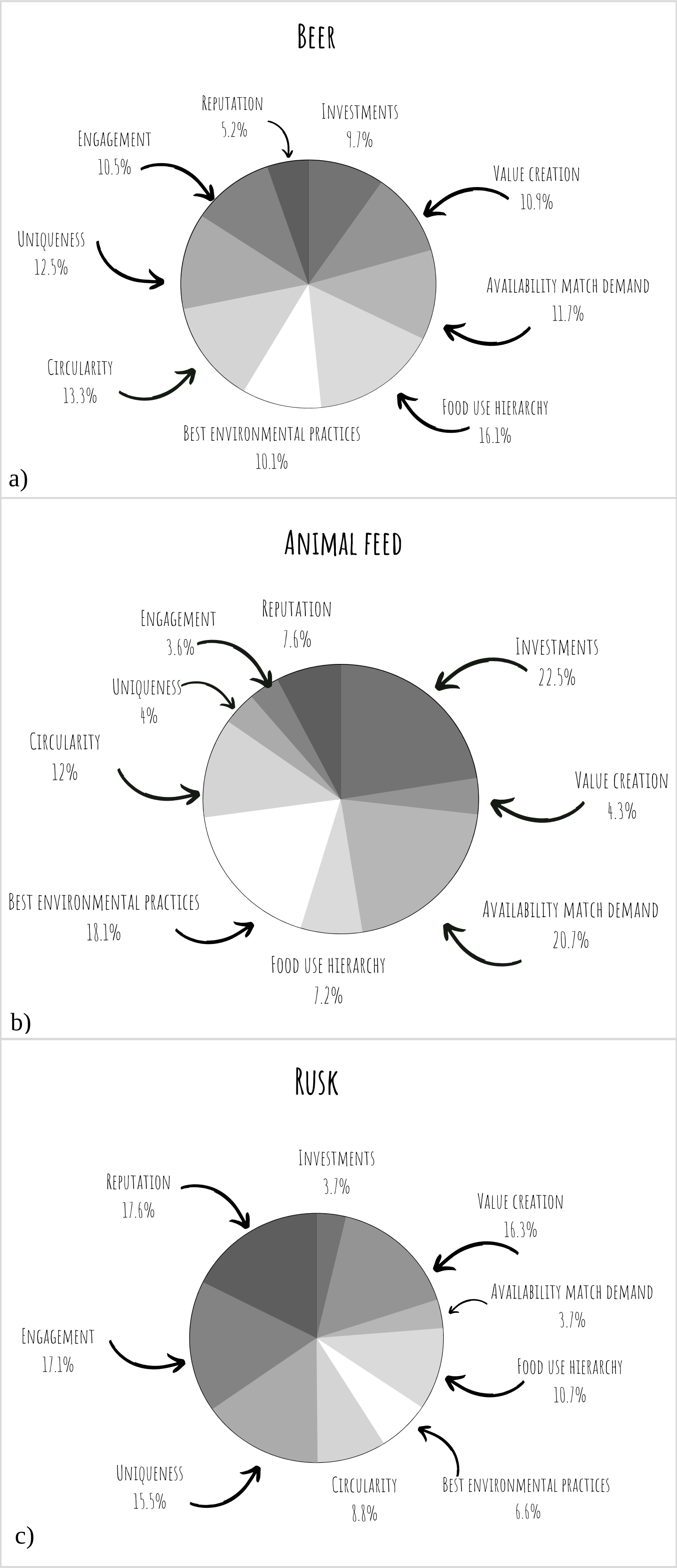


Figure 13: sub-criteria contribution to the overall alternatives' weight. The figure has the scope to provide a visual representation of the sub-criteria importance with respect to beer (Fig. 13.a), animal feed (Fig. 13.b), and rusk (Fig. 13.c).

However, it may take some time to reach a consensus when many people are involved. To avoid it, each participant could fill in questionnaires with their priorities in advance so that the consensus vote occurs depending on most answers given (O’Leary, 1993). Also, Saaty (Saaty et al., 2007) proposed a voting method that considers how strongly people feel about their choices. Luckily, the Upcycling Team, being extremely synergistic, managed to propose a solid judgment after a brief discussion.

5. Method, Part II

5.1. Life Cycle Assessment

“LCA is an objective process to evaluate the environmental burdens associated with a process, product, activity or service system by identifying and quantifying energy and materials used and released to the environment in order to assess the impact of those energy and material uses and released into the environment and to evaluate and implement opportunities to effect environmental improvements” (ISO, 2006a,b). Depending on the scope of the study, it is possible to include in the assessment the entire life cycle (from cradle to grave), encompassing extracting and processing raw materials, manufacturing, transportation and distribution, use, reuse, maintenance, recycling and final disposal, or to develop a partial LCA, (e.g., from cradle to gate) (Fig. 14).

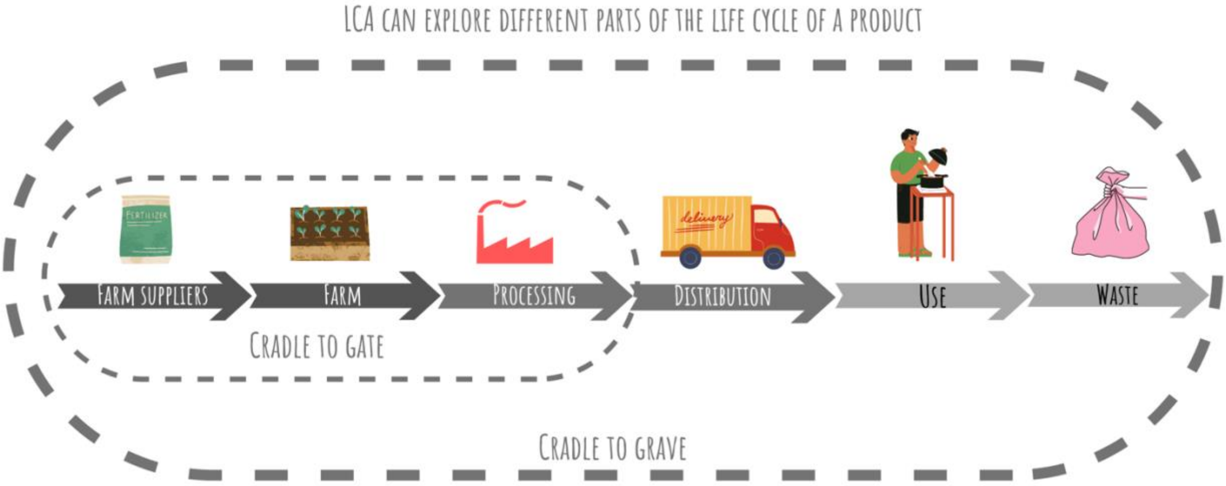


Figure 14: Main phases of the life cycle of a product.

LCA is used to identify the most impacting phases of the life cycle of a product, service or process, thus permitting to improve them and reducing the overall impact and allowing to support policymaking, marketing strategies (avoiding greenwashing), and strategic planning. ISO14040 defines the four-step of an LCA: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Life Cycle Interpretation (ISO, 2006a). The ISO standard 14044 provides more detailed guidance about the different steps (ISO, 2006b) (Fig. 15).

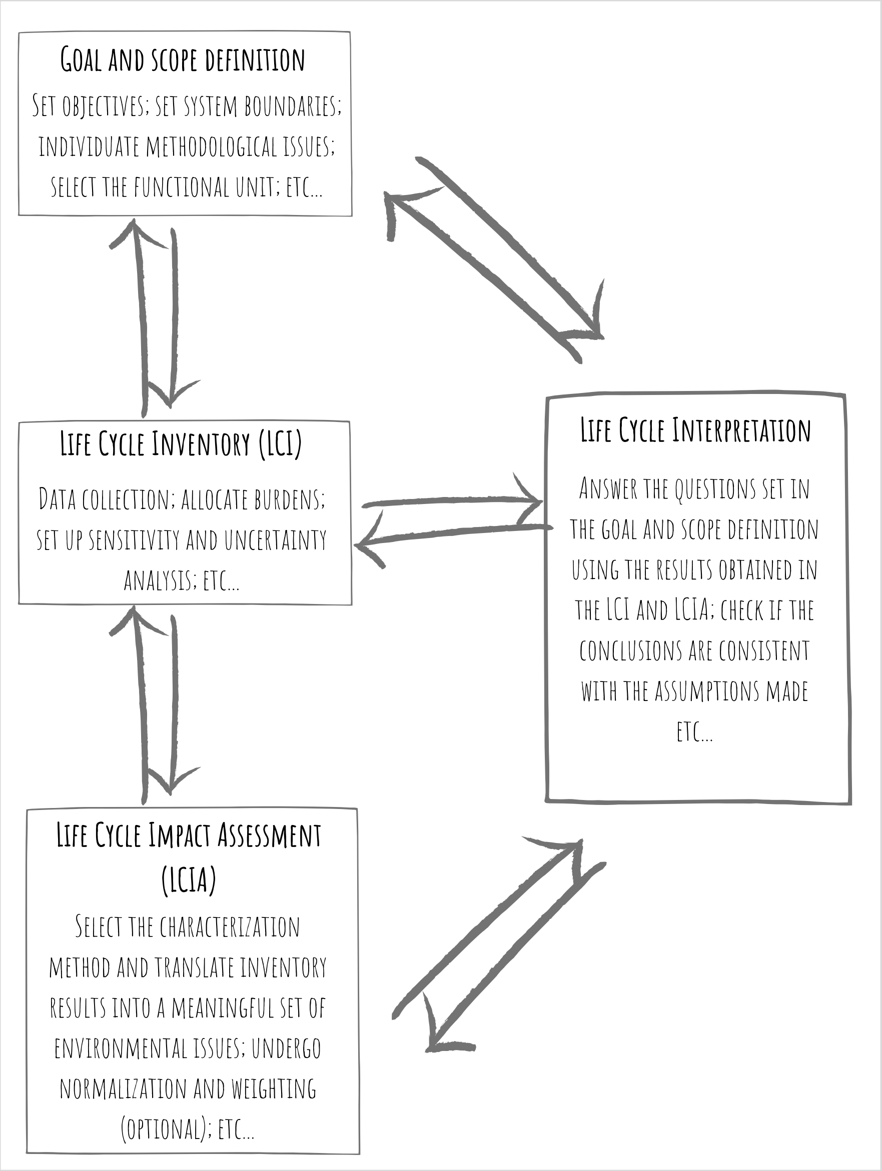


Figure 15: Main phases of a Life Cycle Assessment. Adapted from ISO 14044:2006.

The Goal and Scope Definition step defines the aim of the study, the functional unit selected, and the system boundaries considered. The goal of an LCA study “shall unambiguously state the intended application, the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be communicated” (ISO 2006a,b).

In the LCI step, a realistic model of the system is drafted to represent all the input/output fluxes of material and energy, and the single processes involved. LCI is the most expensive step in time and effort, consisting of data collection, system boundaries adjustment, calculations, data validation, and allocation. It is based on simplified and linear analytic systems, thanks to which materials and energy loops are approximately solved through iteration.

The LCIA consists in selecting the impact categories of interest (e.g., climate change, land use...). Indeed, depending on the chosen method (e.g., ReCiPe 2016 (Huijbregts et al., 2017), IMPACT World+ (Bulle et al., 2019)), different environmental effects can be targeted. Furthermore, some methods propose normalization and weighting factors that allow grouping the impact categories into fewer damage categories to interpret the results better. An example is ReCiPe 2016, which summarizes the seventeen impact categories considered into three categories of damage on, namely, human health, resources availability, and the ecosystem. Anyhow, this is an optional step that implies a considerable degree of subjectivity, and, for this reason, ISO 14044 recommends limiting its application only to analyses that are not disclosed to the public (ISO, 2006b) or, at least, reporting the characterization results. Finally, Life Cycle Interpretation allows discussing the results obtained. More details about the LCA are available in "Integrated Life-Cycle and Risk Assessment for Industrial Processes and Products" (Sonnemann et al., 2018).

5.1.1. Why LCA

With the aim of including environmental considerations into the decision process, the Upcycling Team was proposed to apply LCA for a scientific evaluation of possible alternative strategies to valorize crust bread waste.

The author calculated the environmental impact of the valorization options utilizing the impact category of Global Warming Potential (GWP). GWP evaluation is wide spreading since climate change is a growing public concern (Bala et al., 2010). Indeed, it is among the most urgent climate crisis to mitigate, as underlined by Sustainable Development Goal 13: "Take urgent action to combat climate change and its impacts" (UN, 2015).

The reader may remember that the Upcycling Team built Barilla's *food use hierarchy* considering the study of Sonesson and colleagues that demonstrated that upgrading a by-product into a food product has higher environmental benefits than producing animal feed (Sonesson et al., 2009) (Section 4.1). Therefore, the LCA carried out in this study provides a scientific basis to identify if it is the preferable choice. Moreover, it helps to evaluate the criterion *best environmental practices* quantitatively. Instead, it does not allow measuring *circularity* since no standard methodology is recognized yet (Morone et al., 2020).

The author of this thesis carried out two different LCA studies comparing animal feed production and food processing. Instead, beer production has been excluded from the LCA study since Brancoli and colleagues (Brancoli et al., 2020) already compared the production of beer and animal feed using surplus bread and obtained a comparable environmental impact between the two scenarios. Moreover, beer production is the option that obtained the lowest score in the AHP; thus, it has been excluded from the possible Barilla's bread upgrading options.

The reader is invited to notice that the order proposed to assess the sustainability of the alternatives is the opposite compared to how most researchers do (e.g., they judge the criteria in AHP utilizing LCA results) (Campos-Guzmán et al., 2019). Instead, the author decided to utilize LCA a posteriori (not while using MCDM) and apply it only to the best performing alternatives to limit the time and expenses required by the evaluation.

5.1.2. Standard rusk and feed compared to upcycled rusk and valorized feed respectively

5.1.2.1. Goal and Scope Definition

The manufacturing of an upcycled rusk (UR) made with 80% bread crust and 20% wheat flour is compared to the production of a standard rusk (SR) (100% wheat flour) which is already present in the market as Fette Biscottate Mulino Bianco, a Barilla's brand. Moreover, standard animal feed production (SF) has been compared to the production of valorized animal feed (VF). The manufacturing process itself does not change, while the differences in the product formulations are presented in Table 4 and 5. Note that rusk diminishes its weight by about 60% during the cooking phase.

Table 4: List of ingredients for the standard and the valorized rusk formulations per kg of finished product.

Ingredients	Standard rusk	Valorized rusk	Unit
Wheat flour	1.056	0.212	kg
Yeast paste	0.044	0.044	kg
Sunflower oil	0.034	0.034	kg
White sugar	0.032	0.032	kg
Spring Barley	0.025	0.025	kg
Bread	0.000	0.840	kg
Water	0.449	0.449	kg
Salt	0.013	0.013	kg
Soybean oil	0.002	0.002	kg

Table 5: List of ingredients for the standard and the valorized animal feed formulations per kg of finished product.

Ingredients	Standard feed	Valorized feed	Unit
Wheat bran	0.120	0.074	kg
Faba bean	0.215	0.215	kg
Barley	0.450	0.032	kg
Maize	0.200	0.000	kg
Vitamins	0.008	0.008	kg
Bread	0.000	0.380	kg
Water	$2.010\ 10^{-5}$	$2.010\ 10^{-5}$	kg

The study aims to evaluate to what extend valorizing bread crust may lead to environmental benefits as "in the striving for increased food raw material utilisation it is very important to use a systems perspective since by-product upgrading cannot be considered environmentally friendly *per se*; it depends on the present use of the by-product and on the energy and other inputs needed for the upgrading process itself. So, to avoid sub-optimised solutions, a chain perspective is crucial" (Sonesson et al., 2009).

The system boundaries of the scenarios are set from cradle to factory gate (Fig. 16). The systems under study include raw materials extraction, production, and transport (upstream processes) and the product's industrial process (core process). Downstream processes like packaging, transport to retail, use phase, and end-of-life scenarios have been excluded from the scope of the study since they are assumed to be equal for all the products under investigation. Experts may accept this assumption since the system under study does not need to be the entire life cycle but can be limited to the parts of the system that are affected by the new upgrading process (Sonesson et al., 2009). Indeed, bread crust by-product is introduced in a food product to replace virgin ingredients, but the product itself is not affected by the change. The bread crust is considered as waste and, as such, no impact has been attributed to its production (i.e., "zero burden" approach). The transport of the bread crust to the production plants is excluded. Indeed, the rusk manufacturing plant is assumed to be the same where bread crust by-product is generated, and the animal feed processing plant is assumed to be in Parma, close to the Barilla industrial hub where bread crust is produced.

The functional unit selected is the production of 1kg of product (rusk or animal feed). It is supposed that the nutritional properties of UR and SR, and VF and SF are equal.

The author modelled pork feed production since pork farming is common practice in the Emilia-Romagna region (Battistelli et al., 2020). Data temporal range varies between 2016 for pork feed and 2020 for rusk. The geographical scope is Italy since the manufacturing of the products is assumed to occur there.

The LCA carried out is an attributional comparative LCA. Indeed, to verify the valorization is worth it is always a matter of comparing the present system and the new upgraded one.

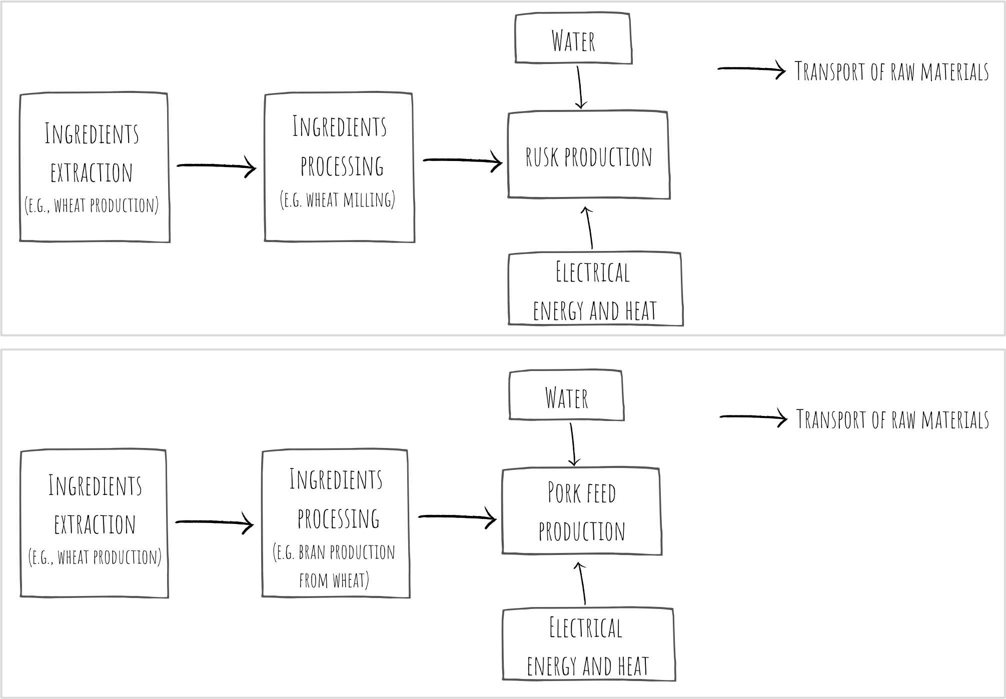


Figure 16: System boundaries of the rusk and pork feed scenarios.

5.1.2.2. Life-Cycle Inventory

For rusk production, the ingredients amount and the energy usage during manufacturing (the foreground system) are based on primary data directly provided by the Barilla company. They are representative for the year 2020. Conversely, data on upstream processes (the background system) are provided by the Ecoinvent database (v3.5) (Wernet et al., 2016) and Agribalyse database (v3.0) (Colomb et al., 2015) (Tab.6). The need to rely on databases occurs because LCA studies require much information, some of which not always directly measurable. Therefore, for background information is standard practice utilizing data contained in databases.

The author modelled the partial life cycle of pork feed production in Italy. The feed recipe used has been formulated by Sirtori and colleagues (Sirtori et al., 2007). They studied a recipe to produce pork feed utilizing bread that allows the pork to fatten as if eating a regular feed recipe. Indeed, they ensured that the conversion rate and the chemical composition parameters such as gross energy, protein content, dry matter and crude fibre remain the same in both recipes. A German company has provided the electric power, the heat, and the water requirements necessary to produce pork feed (Reckmann et al., 2016). The databases mentioned above provide data about the background system per kg of the finished product (Tab.7).

The energy used in all scenarios is assumed to be the Italian energy mix according to the Ecoinvent database. Conversely, the needed heat in rusk production is obtained from natural gas, while the one required for animal feed production comes from diesel (Tab.6,7). Finally, the author assumed that there are no other outputs except for the product obtained. Indeed, output data related to rusk production were available (since provided directly by Barilla), while data related to animal feed were lacking. Thus, to consider the same inputs/outputs in all scenarios and avoid investing time looking for more data, the author decided to consider the product outputs negligible. It is a limitation since gaseous effluents, odours, and solid outputs have not been considered. However, since it is a screening LCA, this assumption is deemed to be acceptable (Bala et al., 2010).

Table 6: Input / Output data related to 1 kg of rusk production.

Input	Standard rusk	Valorized rusk	Unit	Database	Process
Wheat flour	1.056	0.212	kg	Agribalyse	Wheat flour, at industrial mill/FR U
Yeast paste	0.044	0.044	kg	Ecoinvent	Yeast paste, from whey, at fermentation/CH U
Sunflower oil	0.034	0.034	kg	Agribalyse	Sunflower oil, at plant/FR U
White sugar	0.032	0.032	kg	Agribalyse	White sugar, production, at plant/FR U
Spring Barley	0.020	0.020	kg	Agribalyse	Spring Barley, conventional, malting quality, animal feed, at farm gate/FR U
Bread	0.000	0.840	kg		Zero impact
Water	0.449	0.449	kg	Ecoinvent	Tapwater (Europe without Switzerland) | market for | Cut-off, U
Salt	0.013	0.013	kg	Agribalyse	Salt/FR U
Soybean oil	0.002	0.002	kg	Agribalyse	Soybean oil (RoW), soybean oil refinery operation | Cut-off, U
Electricity	0.004	0.004	kWh	Ecoinvent	Electricity, medium voltage, at grid/IT U
Heat	0.088	0.088	MJ	Ecoinvent	Heat, district or industrial, natural gas (RER) | market group for | Cut-off, U
Output	1.000	1.000	kg		

Table 7: Input / Output data related to 1 kg of pork feed production.

Input	Standard feed	Valorized feed	Unit	Database	Process
Wheat bran	0.120	0.074	kg	Agribalyse	Wheat bran, animal feed, at plant/FR U
Faba bean	0.215	0.215	kg	Agribalyse	Faba bean, grain stored and transported, processing/FR U
Barley	0.450	0.032	kg	Agribalyse	Barley, feed grain, conventional, stored and transported, processing/FR U
Maize	0.200	0.000	kg	Agribalyse	Dried grain maize, conventional, national average, at farm gate/FR U
Vitamins	0.008	0.008	kg	Agribalyse	Vitamin and oligo-element, for weaned piglet, at feed plant/FR U
Bread	0.000	0.380	kg		Zero impact
Water	$2.010\ 10^{-5}$	$2.010\ 10^{-5}$	kg	Ecoinvent	Tapwater (Europe without Switzerland) | market for | Cut-off, U
Electricity	$3.900\ 10^{-3}$	$3.900\ 10^{-3}$	kWh	Ecoinvent	Electricity, medium voltage, at grid/IT U
Heat	$5.77\ 10^{-2}$	$5.77\ 10^{-2}$	MJ	Ecoinvent	Diesel, burned in agricultural machinery (GLO) | market for diesel | Cut-off, U
Output	1.000	1.000	kg		

5.1.2.3. Life Cycle Impact Assessment

The characterization of the environmental impact of the products compared is based on the IPCC 2013 GWP 100a method (IPCC, 2013). The Intergovernmental Panel on Climate Change (IPCC) developed the IPCC 2013 GWP 100a impact assessment method to evaluate the Global Warming Potential (GWP) over a time span of 100 years. The time horizon is long enough to assess the cumulative effects of greenhouse gases (GHGs). GWP is measured in mass of carbon dioxide equivalents (kg CO_2eq). Thus, the emissions of GHGs other than CO_2 (e.g., methane) are calculated and expressed as kg of CO_2eq. When LCA is limited to the calculation of the potential contribution to climate change according to the IPCC method, it can be referred to as “carbon footprint” (Junior et al., 2019; Bala et al., 2010; ISO 14067:2018).

The LCA software SimaPro 9.2.0.1 (PRé Consultants, 1990) has been used to model the scenarios. The results obtained are reported in Section 6.

5.1.3. Upcycled rusk compared to upcycled pork feed

5.1.3.1. Goal and Scope definition

The scope of the study is to understand if utilizing bread crust as animal feed has higher or lower environmental benefits than using it to produce a food product suitable for human consumption (i.e., rusk). Thus, it aims at demonstrating that the food use hierarchy utilized by Barilla has scientific foundations and contributes to closing the knowledge gap related to by-products upgrading into food. Moreover, the results help to understand if the qualitative judgements provided by the Upcycling Team while evaluating the alternatives in the AHP under the *best environmental practices* sub-criterion were correct.

The chosen functional unit is 1 kg of valorized bread crust for animal feed production and rusk production. Thus, the ingredients have been normalized to the functional unit selected (Tab.8 and 9). As previously mentioned, the rusk weight reduces by about 60% after cooking.

The system boundaries include raw materials extraction and processing, and the manufacturing stage, excluding packaging, distribution, use phase, and end-of-life scenarios. Cleaning procedures and transport steps have not been considered since they are assumed to be equal in both scenarios. Indeed, bread crust by-product is produced in the same plant where it would be upgraded, while animal feed production would occur within a limited range of km from the bread crust production site.

First, the GWPs of the two valorized scenarios have been compared. Afterwards, the author compared the two standard scenarios. Figure 16 shows the system boundaries of the just mentioned studies. Finally, the difference between the standard and the valorized scenarios have been evaluated. It represents the impact of the upgraded scenarios accounting for the avoided production of standard pork feed or standard rusk. Accounting for the avoided production of the standard products means that the primary production (i.e., extraction and processing of raw materials) of the ingredients replaced by bread crust (e.g., wheat, maize, and others) is subtracted to the overall impact of the upcycled product (Fig.17). In this way, it is possible to obtain the result that allows identifying which is the best upgrading scenario. The geographical scope is Italy. Data are relative to the year 2016 for feed production and 2020 for rusk.

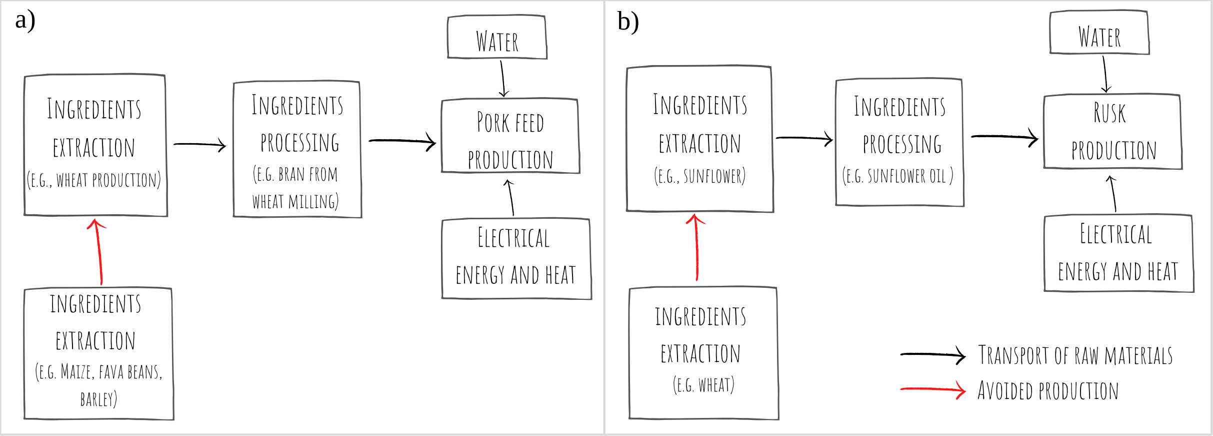


Figure 17: System boundaries of the two compared scenarios: (a) upcycled rusk (b) and upcycled pork feed (b). In both cases, the avoided production of the primary ingredients substituted by bread crust has been considered.

5.1.3.2. Life Cycle Inventory

Data used to model the scenarios are the same in the previous study, but they are normalized to the new functional unit selected. All the information related to data collection are in section 5.1.2.2. In Table 8 and 9, the amount of the ingredients, the processes modelled in the software, and the databases used for background data are reported.

Table 8: Input / Output data related to the production of upcycled rusks made with 1 kg of bread crust.

Input	Standard rusk	Valorized rusk	Unit	Database	Process
Wheat flour	1.257	0.257	kg	Agribalyse	Wheat flour, at industrial mill/FR U
Yeast paste	0.051	0.051	kg	Ecoinvent	Yeast paste, from whey, at fermentation/CH U
Sunflower oil	0.041	0.041	kg	Agribalyse	Sunflower oil, at plant/FR U
White sugar	0.038	0.038	kg	Agribalyse	White sugar, production, at plant/FR U
Spring Barley	0.025	0.025	kg	Agribalyse	Spring Barley, conventional, malting quality, animal feed, at farm gate/FR U
Bread	0.000	1.000	kg		Zero impact
Water	0.532	0.532	kg	Ecoinvent	Tapwater (Europe without Switzerland) | market for | Cut-off, U
Salt	0.016	0.016	kg	Agribalyse	Salt/FR U
Soybean oil	0.002	0.002	kg	Agribalyse	Soybean oil (RoW), soybean oil refinery operation | Cut-off, U
Electricity	0.005	0.005	kWh	Ecoinvent	Electricity, medium voltage, at grid/IT U
Heat	0.104	0.104	MJ	Ecoinvent	Heat, district or industrial, natural gas (RER) | market group for | Cut-off, U
Output	1.190	1.190	kg		

Table 9: Input / Output data related to the production of upcycled pork feed made with 1 kg of bread crust.

Input	Standard feed	Valorized feed	Unit	Database	Process
Wheat bran	0.120	0.074	kg	Agribalyse	Wheat bran, animal feed, at plant/FR U
Faba bean	0.550	0.560	kg	Agribalyse	Faba bean, grain stored and transported, processing/FR U
Barley	1.120	0.830	kg	Agribalyse	Barley, feed grain, conventional, stored and transported, processing/FR U
Maize	0.500	0.000	kg	Agribalyse	Dried grain maize, conventional, national average, at farm gate/FR U
Vitamins	0.020	0.020	kg	Agribalyse	Vitamin and oligo-element, for weaned piglet, at feed plant/FR U
Bread	0.000	1.000	kg		Zero impact
Water	$5.000\ 10^{-5}$	$5.000\ 10^{-5}$	kg	Ecoinvent	Tapwater (Europe without Switzerland) | market for | Cut-off, U
Electricity	$9.750\ 10^{-3}$	$9.750\ 10^{-3}$	kWh	Ecoinvent	Electricity, medium voltage, at grid/IT U
Heat	0,144	0.144	MJ	Ecoinvent	Diesel, burned in agricultural machinery (GLO) | market for diesel | Cut-off, U
Output	2.500	2.600	kg		

5.1.3.3. Uncertainty analysis

Data directly reflect the quality of the LCA results. Data quality must be described and evaluated systematically to allow reproducibility and comprehension by all the stakeholders. The following parameters are usually considered: temporal coverage, geographical coverage, technological coverage, precision, completeness, consistency, reproducibility, data sources, and the uncertainties related to the assumptions. Uncertainty analysis is applied to determine how the intrinsic variability of the parameters and the quality of the data used in modelling the scenarios may affect the resulting outcomes (PRé, 2015).

The Ecoinvent database quantifies its life cycle inventory's uncertainty distribution and statistics (e.g., average and standard deviation). Thus, the background data the author used in this study (e.g., wheat milling process) come already with a certain level of uncertainty. However, foreground data uncertainty must be calculated. How does uncertainty in the input data can be specified? Ecoinvent always provides a standard value together with uncertainty information. The standard value is interpreted as the "best guess" value (or most probable value). If this best guess value is determined by sampling many different measurements, this is usually the mean value of a (log)normal distribution. A characteristic of a lognormal distribution is that the square of the geometric standard deviation covers the 95% confidence interval. In the case of the foreground data of the study, data are not taken from a large sample of measurements. Thus, the geometric standard deviation must be estimated with the Pedigree Matrix (Weidema et al., 1996).

The Pedigree Matrix is generally composed of six data quality indicators: reliability, completeness, temporal correlation, geographical correlation, technological correlation, and the basic uncertainty factor. A score from 1 to 5 is attributed to each of the first five indicators depending on the data quality (5 means the data quality for the indicator is low, 1 that the data quality is high). Afterwards, an uncertainty factor is attributed to each score (e.g., if reliability has a score of 1, the uncertainty factor is 1.00) (Tab.10). Combining the indicators' scores provides an overall uncertainty factor. Furthermore, the basic uncertainty factor that the reader finds in "Introduction to LCA with SimaPro" (Pré, 2015; pag.41), must be added.

Table 10: Pedigree Matrix adapted from PRé, 2015. Source: Weidema et al., 1996.

Indicator	Score				
	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g., by industrial expert); data derived from theoretical information (stoichiometry, enthalpy, etc.)	Non-qualified estimate
Uncertainty factor	1.00	1.05	1.10	1.20	1.50
Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered OR >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered OR some sites but from shorter periods	Representativeness unknown or data from a small number of sites AND from shorter periods
	1.00	1.02	1.05	1.10	1.20
Temporal correlation	Less than 3 years of difference to our reference year	Less than 6 years of difference to our reference year	Less than 10 years of difference to our reference year	Less than 15 years of difference to our reference year	Age of data unknown or more than 15 years of difference to our reference year
	1.00	1.03	1.10	1.20	1.50
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from smaller area than area under study, or from similar area	Data from area with slightly similar production conditions	Data from unknown OR distinctly different area (north America instead of Middle East, OECD-Europe instead of Russia)
	1.00	1.001	1.02	1.05	1.10
Further technological correlation	Data from enterprises, processes and materials under study (i.e., identical technology)	Data from processes and materials under study (i.e., identical technology) but from different enterprises	Data on related processes or materials but same technology, OR data from processes and materials under study but from different technology	Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology	Data on related processes or materials but on laboratory scale of different technology
	1.00	1.05	1.20	1.50	2.00

Once the uncertainty factor and the basic uncertainty factor have been obtained, the squared geometric standard deviation is calculated (Equation 3) (PRé, 2015).

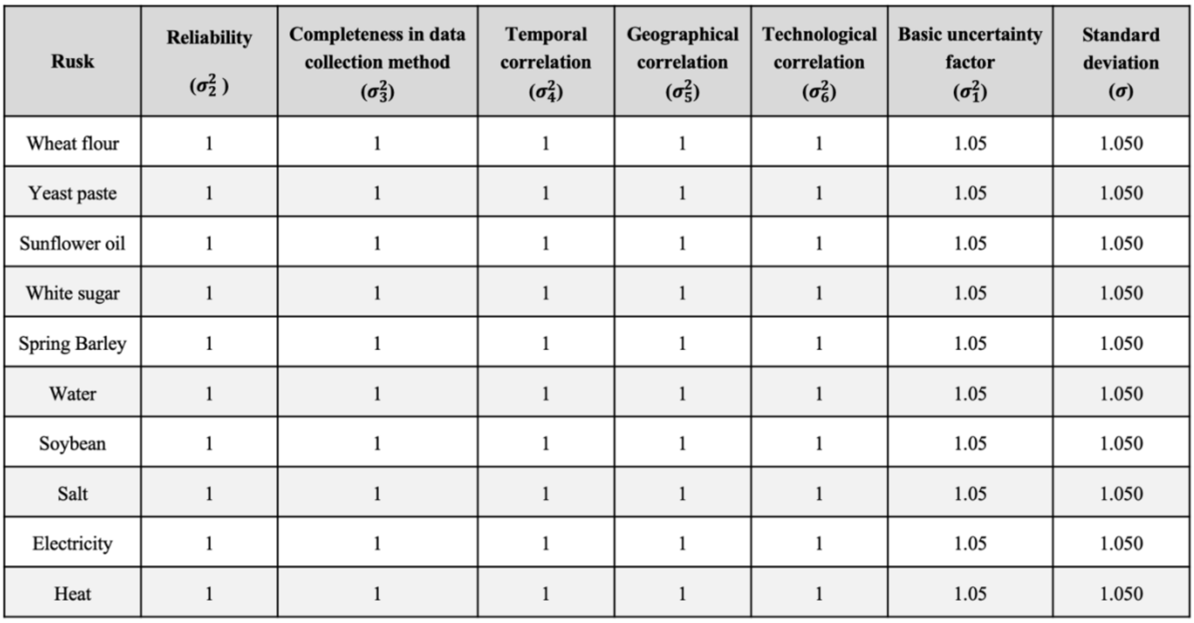
$$\sigma^2 = \sum_{n=1}^{6} = {\sigma^2}_{\mathrm{n}} \qquad \text{(Eq.3)}$$

The factors σ_2^2 to σ_6^2 refer to the uncertainty factors in the reliability (1), completeness (2), temporal correlation (3), geographical correlation (4) and further technology (5). The factor σ_1^2 refers to the basic uncertainty factor.

For more information about how the uncertainty calculation works, it is suggested to read “Data quality guideline for the Ecoinvent database” (Weidema et al., 2013).

The uncertainty of the foreground data for rusk and animal feed has been arbitrarily individuated utilizing the Pedigree Matrix. The Barilla company has provided data about rusk production; thus, they are of excellent quality. The author attributed the highest score to all data quality indicators (1;1;1;1;1). The factors from σ_2^2 to σ_6^2 corresponding to score 1, the basic uncertainty factor, and the calculated standard deviation are reported in Table 11. As basic uncertainty factor, the author selected 1.05 since it refers to “thermal energy, electricity, semi-finished products, and working materials” (Pré, 2015); thus, it is the value that best describes the system.

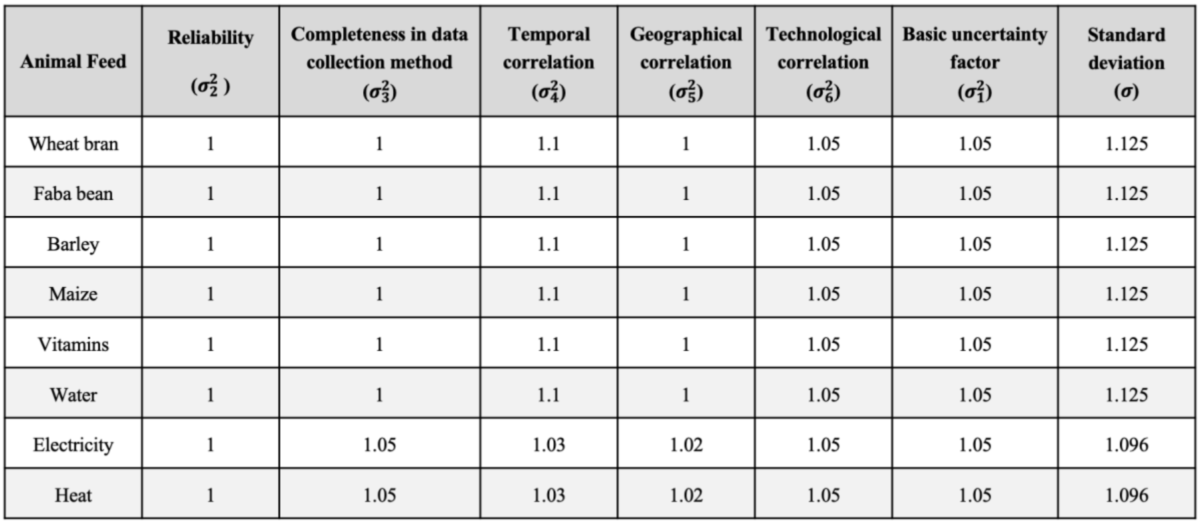
Table 11: Pedigree Matrix arbitrary scores for the foreground data of rusk production and calculation of the standard deviation with Eq.3.



Rusk	**Reliability (σ_2^2)**	**Completeness in data collection method (σ_3^2)**	**Temporal correlation (σ_4^2)**	**Geographical correlation (σ_5^2)**	**Technological correlation (σ_6^2)**	**Basic uncertainty factor (σ_1^2)**	**Standard deviation (σ)**
Wheat flour	1	1	1	1	1	1.05	1.050
Yeast paste	1	1	1	1	1	1.05	1.050
Sunflower oil	1	1	1	1	1	1.05	1.050
White sugar	1	1	1	1	1	1.05	1.050
Spring Barley	1	1	1	1	1	1.05	1.050
Water	1	1	1	1	1	1.05	1.050
Soybean	1	1	1	1	1	1.05	1.050
Salt	1	1	1	1	1	1.05	1.050
Electricity	1	1	1	1	1	1.05	1.050
Heat	1	1	1	1	1	1.05	1.050

The data quality of the feed ingredients is slightly lower than the rusk one. Indeed, data are from a recipe developed in Italy in 2007; thus, the temporal and technological correlations are less accurate. However, the author assumed that data are complete and reliable since the recipe was developed to ensure the desired pork growth, and it does not change over time. Pork feed ingredients got the following scores (1;1;3;1;2) that translate into the uncertainty factors of Table 12. Finally, data related to the electrical energy and the heat used to produce pork feed are secondary data gathered in the literature. However, they were provided directly by a German company in 2016. Thus, the author assumed that they were reliable. Instead, completeness, temporal, geographical, and technological correlations have been considered to have a lower score (1;3;2;3;2). Table 12 reports the uncertainty factors and the standard deviations calculated for animal feed data.

Table 12: Pedigree Matrix arbitrary scores for the foreground data of pork feed production and calculation of the standard deviation with Eq.3.



Animal Feed	**Reliability (σ_2^2)**	**Completeness in data collection method (σ_3^2)**	**Temporal correlation (σ_4^2)**	**Geographical correlation (σ_5^2)**	**Technological correlation (σ_6^2)**	**Basic uncertainty factor (σ_1^2)**	**Standard deviation (σ)**
Wheat bran	1	1	1.1	1	1.05	1.05	1.125
Faba bean	1	1	1.1	1	1.05	1.05	1.125
Barley	1	1	1.1	1	1.05	1.05	1.125
Maize	1	1	1.1	1	1.05	1.05	1.125
Vitamins	1	1	1.1	1	1.05	1.05	1.125
Water	1	1	1.1	1	1.05	1.05	1.125
Electricity	1	1.05	1.03	1.02	1.05	1.05	1.096
Heat	1	1.05	1.03	1.02	1.05	1.05	1.096

Once the standard deviation has been calculated, we can model the uncertainty scenario. A standard method employed to evaluate system uncertainties is the Monte Carlo Simulation. This statistic method consists in generating and propagating uncertainties to the system variables. For a reasonable number of simulations (e.g., 10.000), following an algorithm, a result can be described as a probability distribution characterized by average values and standard deviations. The simulation replicates evaluations by changing parameters inside the confidence interval (the higher the interval, the higher the data uncertainties).

The result of the Monte Carlo analysis obtained by running 10.000 times the simulation in the software SimaPro is reported in Section 6.

5.1.3.4. Life Cycle Impact Assessment

The characterization of the environmental impact of the products is based on the IPCC 2013 GWP 100a method (IPCC, 2013) (section 5.1.2.3).

6. Results and discussion

6.1. Life Cycle Interpretation

The first study (Section 5.1.2) shows that the scenario involving the production of UR has a lower GWP compared to the SR. Indeed, the production of 1 kg of SR emits 0.60 kg CO_2eq, while 1 kg of UR emits 0.31 kg CO_2eq, representing half the standard product's emission (Fig.18). This is mainly due to the avoided production of flour from wheat milling. Indeed, wheat milling is an energy-intensive step in raw material transformation (Roy et al., 2009). In the SR production, the impact of wheat milling accounts for 61% of the total GWP, whereas in the UR, it accounts for only 24%. This result highlights a consistent contribution of the milling process to the final impact.

Knowing that the UR has a lower GWP than the SR is essential information since it motivates the valorization of bread crust into a food product. Indeed, considering the annual rusk production at the Barilla plant, a shift towards upcycled ingredients would allow saving 5,464,399 kg di CO_2eq, which correspond to 90,355 tree seedlings grown for ten years (EPA, 2021).

The author obtained that utilizing bread crust for animal feed provides environmental benefits in terms of GWP. The production of SF emits 0.25 kg CO_2eq, while the VF only 0.14 kg CO_2eq (Fig.19). Indeed, maize and barley productions have the highest GWP. Since bread crust completely substitutes maize and reduces the barley content, the lower impact on climate change of the VF is justified.

To summarize, both alternatives present a lower GWP than standard production scenarios.

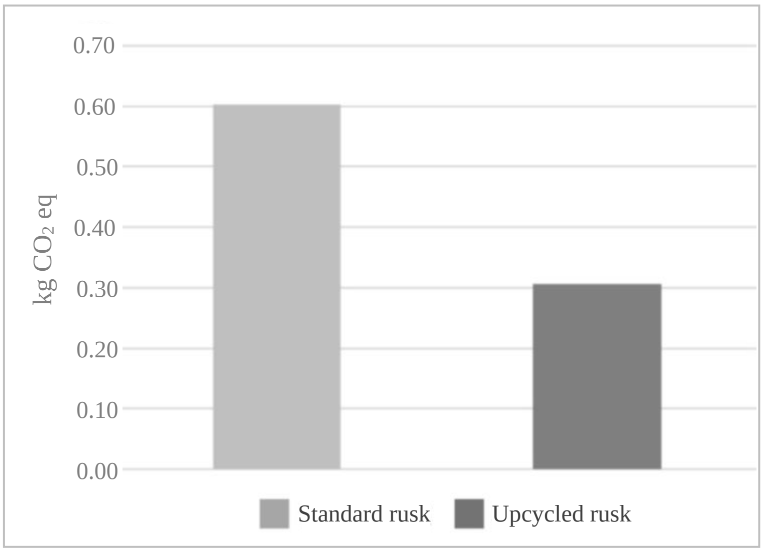


Figure 18: Global warming potential of 1kg of upcycled and standard rusk.

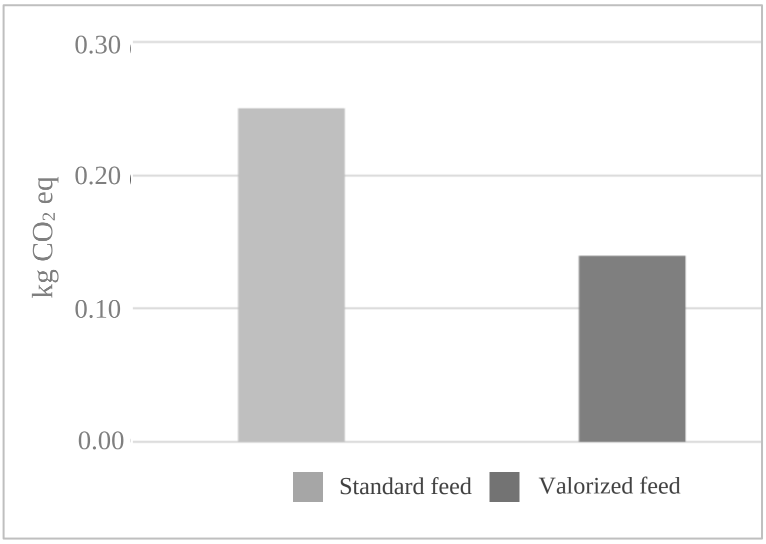


Figure 19: Global warming potential of 1kg of standard and valorized animal feed.

Let the author now consider the second study (Section 5.1.3).
The valorization of 1 kg of bread crust allows to produce 2.60 kg of pork feed and 1.19 kg of rusk. It emerged that the GWPs of the two valorization scenarios are comparable. Indeed, VF has a GWP of 0.36 ± 0.02 kg CO_2eq, while the UR contributes to climate change with 0.37 ± 0.02 kg of CO_2eq (Fig.20).

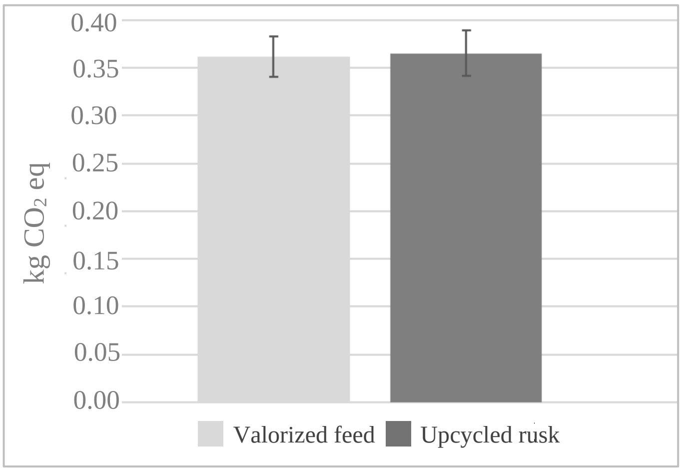


Figure 20: Global Warming Potential of the two valorized scenarios per kg of bread crust and relative data uncertainty.

According to the results, it is impossible to state which alternative performs better among the two. Indeed, UR has a 55% probability of having higher GWP than VF, and VF has a 45% probability of having higher GWP than UR (Fig.21). The closer the probability that the impact of one process overcomes the impact of the other is to 50%, the higher is the uncertainty associated with the result.

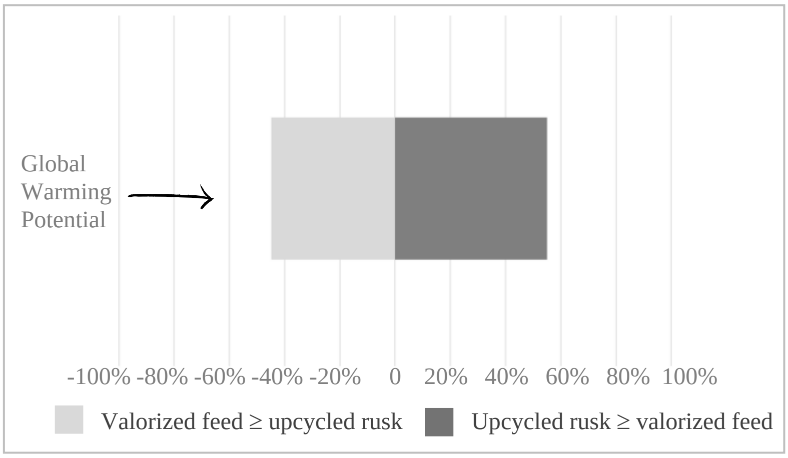


Figure 21: Uncertainty associated with the result. Probability of valorized feed of having higher GWP than upcycled rusk and vice versa.

Nevertheless, if we compare the production of SF (2.50 kg per kg of bread crust) to SR (1.19 kg per kg of bread crust), we obtain that rusk production results in a higher release of GHGs emissions in the atmosphere: 0.72 ± 0.05 kg CO_2eq for rusk and only 0.63 ± 0.03 kg CO_2eq for animal feed (Fig. 22). The uncertainty is low: 5.44% for animal feed and 6.52% for rusk.

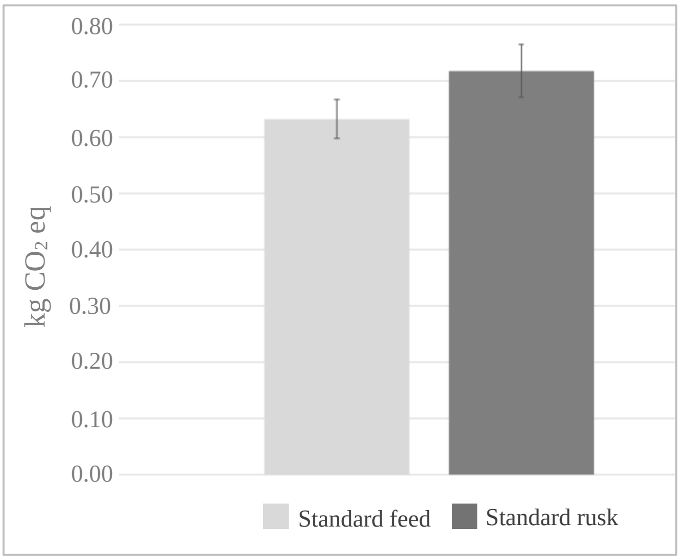


Figure 22: Global Warming Potential of the standard scenarios per kg of bread crust and relative uncertainty.

The analysis confirms that it is highly probable that SR production is more impacting than producing SF. Indeed, in the 95% of cases, SR has a higher impact than SF (Fig.23). If a process results more impacting than the other in the 100% of the cases it means that uncertainty is not high enough to affect the results. In this case, the resut is not affected.

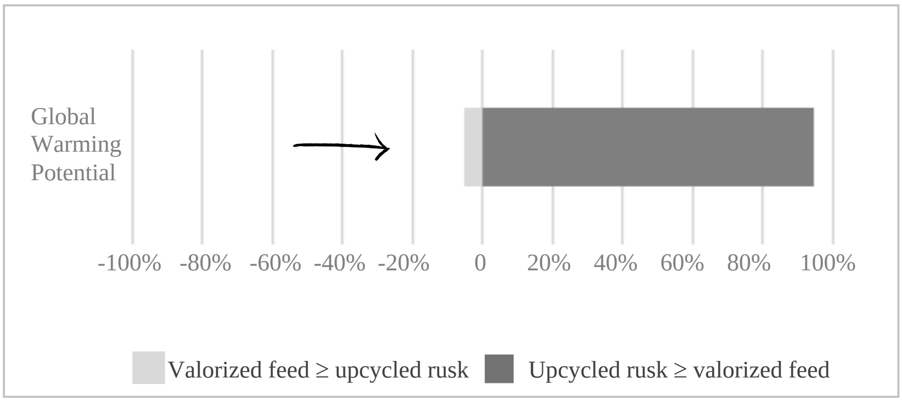


Figure 23: Uncertainty associated with the result. Probability of standard feed of having higher GWP than standard rusk and vice versa.

What happens when we calculate the GWPs of the upcycled scenarios, and we consider the avoided production of the standard products? Accounting for the avoided production of the standard products means that the primary production (i.e., extraction and processing of raw materials) of the ingredients replaced by bread crust (e.g., wheat, maize, and others) is subtracted to the overall impact of the upcycled product. We obtain GWPs with negative values, which indicates that producing upcycled products provide environmental benefits (Fig.24). Moreover, Figure 24 shows that the production of UR is better than VF when the avoided production of the raw materials substituted by bread is considered. Indeed, it allows to save more GHG emissions per kg of bread crust utilized: - 0.35 kg CO_2eq and - 0.28 kg CO_2eq, respectively. Indeed, since the production of SR has a higher impact on the GWP due to the wheat milling process, substituting flour with bread crust results in lower use of wheat flour and, thus, high environmental savings.

Interestingly, the conclusions would have been different if the assessment had been performed without the systems perspective (i.e., without including the decreased use of raw materials). Using bread crust for snack production would have come out equal to using it for feed (Fig.21). Thus, the systems perspective gives a deeper analysis and understanding of the environmental effects of upgrading by-products (Sonesson et al., 2009).

The study demonstrates that the Team's choice to place "upgrading food by-products into new food products" in a preferred position in the *food use hierarchy* than valorizing it as animal feed is legitimate (section 4.1). Indeed, producing an upcycled product such as rusk provides a higher reduction of GHG emissions than producing animal feed; thus, it resulted in higher environmental savings.

Considering the AHP, the feed has been ranked higher than rusk production during the pairwise comparison of the alternatives under the sub-criterion *best environmental practices* (Section 3.1.2.5.). Instead, this study shows that producing an UR brings higher environmental benefits than those estimated for VF. Thus, rusk should be given a higher score than feed for that criterion in the AHP. However, rusk already resulted in the preferred option, and the misevaluation does not influence the result.

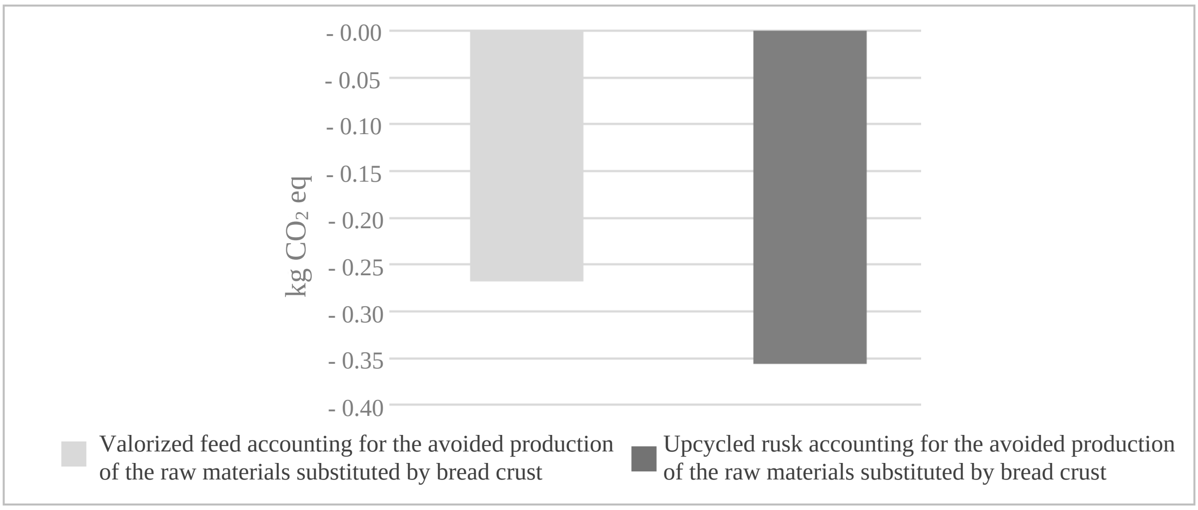


Figure 24: GWPs of the upcycled scenarios accounting for the avoided production of primary raw materials.

Nevertheless, the transport, the packaging, the use phase, and the end-of-life scenarios have not been evaluated. Thus, the author cannot confirm with certainty that rusk would result better even when considering the entire life cycle of the products. Anyhow, a complete study that involves downstream processes like packaging production should be carried out. However, it is demonstrated that the environmental impact of packaging is relatively small compared to the food they contain (Grönman et al., 2013). Consequently, the author decided to exclude it from the study.

Moreover, the author should use different characterization methods to evaluate other impact categories, and primary data for upstream processes and animal feed production should be collected. However, such a study would require time, human resources, and financial expenses. Thus, in agreement with Bala and colleagues (Bala et al., 2010), the author, and especially the company, believe that the results obtained are sufficient to carry out a screening process.

6.2. Sensitivity analysis

The UR is assumed to contain 80% of bread crust and 20% of flour. Barilla’s RD&Q managers tried several recipes with this amount of bread. However, sensory investigations with consumers are still to be made. In case of scarce consumers acceptance, a lower amount of bread may be added to keep the organoleptic and texture properties of the UR equivalent to the

SR. Which is the breakeven point? Can the product developers substitute only 50% of the flour with bread crust and still guarantee that the GWP of rusk production is lower than that of animal feed? To reply to this question, the author modelled the partial carbon footprint of 1.19 kg of rusk made with 50% wheat flour and 50% bread crust using 1 kg of bread crust as a functional unit. She also considered the avoided impact of the primary production of the standard formulation's ingredients substituted by bread crust. Moreover, she assumed that the nutritional properties would not change. It resulted that utilizing a lower amount of flour in the product formulation saves 0.35 kg CO_2eq. Instead, the amount of crust in the animal feed recipe remains constant, otherwise the nutritional properties would change. Thus, valorized animal feed production always leads to saving 0.27 kg CO_2eq (Fig.24). Therefore, it is possible to conclude that even a lower amount of bread crust in the rusk formulation would not affect the environmental preference for this scenario (Fig. 25).

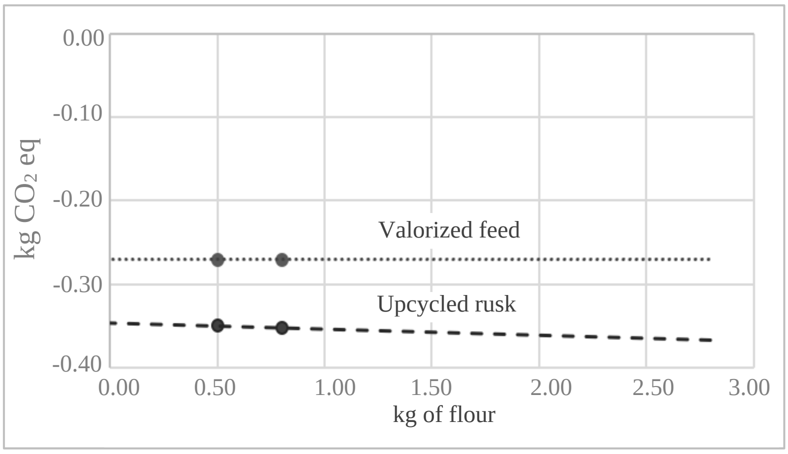


Figure 25: Sensitivity analysis. Even diminishing the % of flour in the upcycled rusk formulation allows it to have a lower GWP compared to animal feed. The avoided production of the standard products has been considered.

7. Design Thinking

The author would like to mention that she attended sessions on Design Thinking during the internship. Design Thinking, "put simply, is a discipline that uses the designer's sensibility and methods to match people's needs with what is technologically feasible and what a viable business strategy can convert into customer value and market opportunity" (Brown, 2008). In particular, she collaborated with an inter-functional team to investigate what customers would expect from an upcycled food product. They created products' prototypes and interviewed consumers.

It emerged that consumers expect a healthy product that is tasty and characterized by sustainable packaging (even if consumers perception of sustainable packaging not always matches with LCA results) (Boesen et al., 2019).

However, it emerged that not everyone is willing to "eat waste". Therefore, the author believes that Barilla should organize awareness campaigns through advertisements, social networks, and events to sensitize consumers.

Moreover, it emerged that people would be willing to buy an upcycled product that results from the collaboration between Barilla and a Small-Medium Enterprise (SME) (e.g., local farmers, family-owned companies), thus benefiting the local community. Therefore, consumers expect corporates to adopt a sustainable design approach, one that encompasses ethical and environmental aspects.

Thus, when developing an upcycled product, Barilla employees should consider the insights obtained during Design Thinking and those obtained with LCA. The former to shape the product on consumers desire, the latter to shape the product on eco-design. Indeed, "decisions made at the product design stage radiate throughout the food system, from farmers to consumers, impacting economic, societal, and environmental outcomes. To ensure these impacts are positive, at every stage of the design process there needs to be a continuous oscillation between zooming in to the consumer's needs and zooming out to consider the environmental and societal impacts" (Ellen MacArthur foundation, 2021).

8. Author's thoughts

While carrying out her internship, the author had the chance to present the project to the first line of Barilla's managers. For her, it has been the best accomplishment! She performed as the interface between science and people, matching academics knowledge to business needs. Moreover, she brought these crucial topics to the attention of managers of different sectors to trigger a systemic change. It is what she would have expected from a perfect internship. Indeed, to reverse climate change and related issues and make a transformative change, leadership must be involved (Maranesi et al., 2020). If leaders pursue ethical leadership, there are more chances corporate can make a difference in the fight against climate change. The road is still long and uphill, but the important thing is to start to reach the finish line.

9. Conclusions

Food wastage along the FSC represents a massive issue in today's society. It causes damages to the environment, society, and the global economy. However, each stakeholder can make a difference to reverse the situation. Indeed, if passionate and willing to act, leaders and employees can drive companies towards the circular economy, the economic system that allows sustainable development.

This thesis aimed to raise awareness among the Barilla managers and employees about the importance of developing the company sustainably. Barilla should valorize its by-products by maximizing financial performances, bringing social benefits, and generating null impact to the environment.

The author interviewed the employees to understand their point of view and the state of the art of by-product valorization. She understood that too many different ideas hindered any valorization alternative to take off.

Thus, she decided to settle the basis for upcycling, selecting the most relevant criteria that usually push or stop a project to be implemented. The Upcycling Team has defined those criteria as an inter-functional team that voluntarily raised its voice towards implementing the circular economy. However, the criteria should be revised to reach the TTL.

Afterwards, the author proposed a method to judge the different alternatives (food, feed, and beer production) on the conflicting criteria selected. She adopted the Analytic Hierarchy Process (AHP), a tool for decision making. To restrict the study's goal, she focused on bread crust valorization, but the methodology could apply to any Barilla's by-product.

To evaluate if the judgements done under the ecology's criterion were correct, she carried out a partial Life Cycle Assessment (from cradle to factory gate). The assessment allowed her to compare the production of a snack with the production of animal feed using bread crust. Instead, beer production has been excluded from the study since the AHP showed it is the alternative that the least maximizes economic, social, and environmental aspects.

The AHP and the LCA results combined, suggested that producing an upcycled rusk utilizing crustless bread by-products would maximize the three pillars of sustainability, bringing to the company profit, ethics, and reducing GHG emissions. The production of an upcycled food product could bring environmental benefits and social benefits (e.g., food security). Moreover, the company's reputation could increase, especially among the new generations more attentive to sustainability (Zhang et al., 2021). Finally, it would bring economic benefits due to the savings in raw materials production and energy use. Furthermore, it would contribute to the creation of a new business, thus increasing the company’s revenues. Besides, if Barilla decides to continue utilizing its by-product for animal feed production, such a choice would not be harmful from a GWP point of view. However, valorizing bread crust as animal feed might bring lower social and economic benefits to the company. Also, since an external company would produce animal feed, the overall carbon footprint of Barilla would not appear diminished. Conversely, considering that the upcycled rusk would be produced at the Barilla plant, the company would be able to reduce its carbon footprint, thus growing even more in reputation.

In Barilla, they must now only implement the product. The Upcycling Team believes that the product must follow the concept of eco-design to be coherent with the Barilla mission "Good for you, good for the planet" and coherent with the valorization process itself.

Therefore, the product's manufacturing should be highly efficient in energetic terms and in limiting waste generation. If the generation of scraps is unavoidable, experts should plan to utilize them during the rusk design stage. Indeed, the reader learnt from the food use pyramid that prevention is the best weapon for fighting food waste. Thus, process designers’ goal is to manage by-products before they become waste.

Another vital consideration regards packaging. If Barilla produces a sustainable product, it must maintain sustainability in its packaging (MacArthur, E., 2017). Over-packaging must be avoided, and the filling rate maximized. Moreover, the material should be 100% recyclable or compostable, and it must not contain toxic substances.

Utilizing the AHP to select the best valorization option, applying the LCA to verify the screening process and combining the results to the Design Thinking findings allows Barilla employees to understand how to launch a valorized product in the market. However, consumers’ willingness to purchase must still be investigated. Anyhow, it is suggested to start an awareness campaign to sensitize customers on food waste.

Furthermore, to increase the success rate of industrial innovation, policymakers should release regulative and legislative guidance on food by-products valorization. Indeed, food safety must be guaranteed throughout the whole process.

Finally, Barilla's experts could consider more quantitative studies related to the equity and economy criteria using Life Cycle Costing (LCC) (Woodward, 1997) and Social Life Cycle Assessment (S-LCA) (Jørgensen et al., 2008).

Barilla and the Upcycling Team are ready for the future. A future where waste is a resource for novelty products, where energy is renewable and managed efficiently. A future where processed food is nutritious, healthy, sustainable, and raw materials are obtained following the rules of nature.

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