Multi-objective approach to sustainability in fashion

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***Abstract*—Fashion industry is accountable for about 10% of global greenhouses emissions and 20% of water pollution. This research tries to define the sustainability of cotton fiber in terms of policies towards workers of the supply chain and wise handling of pollutant elements involved in the process of cotton growing and transportation. Once the variables to take into account and their ranges have been defined, a Non-dominated Sorting Genetic Algorithm has been performed to identify solutions that, while maximizing the overall sustainability, keep cotton prices to acceptable levels. The obtained Pareto front can be compared with the indexes that have been assigned to 10 countries representative of different levels of sustainability.**

***Index Terms*—Sustainability index, Multi-objective optimization methods, Fashion, Cotton.**

I. Introduction

The European Parliament [1] estimates that the fashion industry and the connected textile production account for the 10% of the global carbon emission and 20% of the global water pollution. All the lifecycle's stages of a textile product, from the growth of natural fibers or the production of synthetic ones to the washing, steaming and dying while in the hand of the final consumer, are characterized by greenhouse gases emissions, soil degradation, micro-plastic releases, groundwater pollution and waste of water, among many other drawbacks. The fast fashion industry deeply changed both shopping behavior and textile production: it is estimated that since 1996 the amount of kilograms of clothes bought per person in Europe increased by 40% [2], reducing the lifetime of fashion products and increasing the volume of clothes that are yearly dumped into landfills. At the same time the request for low-cost clothing imposes a strong pressure over textile production, pushing the manufacture to countries with weak labour regulations and cheap manpower and consequently threatening workers rights and safety.

While this trend has to be faced taking steps back in the way textile products are consumed, it is also important to analyze the stages composing the lifecycle of a textile product and optimize them increasing their sustainability. For this research the cotton fiber was taken into consideration, as it is one of the most used in clothing manufacturing. Thanks to several studies aimed at increasing cotton sustainability [3][4] (which also contributed in realizing an Organic Cotton Standard), data about the emissions connected to its growth and fiber production are easily available.

The purpose of this research is to solve the multi-objective optimization problem of minimizing the price of cotton fiber while maximizing its sustainability, defined in a simplified way including values related to production, worker rights and transportation, (more details in the II section) using Non Dominated Sorting Genetic Algorithm (NSGA-2).

TABLE I: Sustainability index and prices (€) values

Country	Transport	Worker	Production	Price	Total
India	6.2	0.56	3.05	2.36	2.65
Peru	7.6	4.72	3.17	2.28	4.38
China	3.9	3.18	2.31	2.44	2.85
Bangladesh	3.0	1.09	3.93	2.03	2.8
USA	4.88	6.81	6.72	3.04	6.48
Vietnam	4.35	2.25	3.72	1.68	3.3
Italy	10	6.17	6.39	3.21	6.86
Uzbekistan	3.6	1.71	0.67	1.68	1.47
Turkey	3.58	2.5	5.68	2.19	4.25
Egypt	4.06	4.18	5.65	3.37	4.9

II. Methodology

In the textile and clothing sector, a set of instruments for the standardized measurement of the value chain sustainability, called *Higg Index*, is currently used to evaluate the social and environmental performances as well as the impact of the product [5]. Starting from an investigation on the key aspects of such index and focusing on its capability to measure sustainability relying on multiple categories, the index S_{index} designed in this research is made up of the joint contribution of three scores related to production (S_p), workers' conditions (S_w) and transportation (S_t), which are combined by means of a weighted sum:

$$S_{\text{index}} = 0.5 \cdot S_p + 0.35 \cdot S_w + 0.15 \cdot S_t \qquad (1)$$

The sustainability index is computed for each of the examined country and it is expressed in the range [0,10] so that the higher the value, the more sustainable is that country. The obtained results are visible in Table I.

A. S_p - Production Index

$$S_p = 6 \cdot \text{CO}_{2\text{fertilizer}} + 4 \cdot \text{H}_2\text{O}_{\text{waste}}$$

According to *Defra* [6] the stage that goes from growing cotton balls to the spinning necessary to obtain the cotton yard is the second most expensive phase of a cotton fabric lifecycle in terms of energy consumption after the customer use. It accounts for 13% of the total energy, while the costumer's use accounts for the 80% of it. Given that the costumer use goes beyond the scope of this research, it has been decided to realize a Production Index S_p and assign it the highest weight

TABLE II: Fertilizer to CO_2

Kg of fertilizer	$CO_{2\text{fertilizer}}$
$547 \leq x < 662$	1 - 0.903
$663 \leq x < 778$	0.84 - 0.731
$779 \leq x < 894$	0.661 - 0.542
$895 \leq x < 1010$	0.461 - 0.332
$1011 \leq x < 1126$	0.241 - 0.102
$x \geq 1127$	0

in the final Sustainability Index S_{index}. This production index takes into consideration the quantity of average fertilizer used in a certain country ($CO_{2\text{fertilizer}}$) and the average water waste in cotton cultivation for each country (H_2O_{waste}).

1) $CO_{2\text{fertilizer}}$: Fertilizers and pesticides applied on cotton fields are the most pollutant elements in cotton production, responsible for soil degradation, groundwater pollution and GHG emissions. Different studies (such as Cotton Incorporated, 2009 or Australian Cotton Lifecycle Assessment, 2009) tried to estimate the amount of CO_2 emitted per kg of fiber produced, but they all took into account different parameters and countries (with peculiar necessities), leading to varying estimates. WWF India [3] observed that, with the same environmental conditions, not only higher fertilizer applications were not related to higher amount of seed cotton yield but also that farm plots applying balanced fertilizer quantities observed an increase in the production.

Based on the WWF report [3], that compared traditional cotton cultivation (TC) and cultivation with better management practices[1] (BPM) a range of yearly applied kg of fertilizer x was defined, going from the minimum amount observed in BPM plots to the maximum observed in TC plots. A multiplier m was estimated to be able to translate the kg of fertilizer applied into kg of emitted CO_2 and normalized the obtained score in a range going from 1 (for cultivation applying balanced amount of fertilizer) to 0 (for unsustainable cultivation). The formula to obtain this score is the following:

$$CO_{2\text{fertilizer}} = 1 - \frac{(x \cdot m) - (547 \cdot 1.88)}{(1127 \cdot 2.87) - (547 \cdot 1.88)}$$

Thanks to a report from UNESCO [4] it was possible to derive average amount of fertilizer application per country and therefore compute country-specific scores for the $CO_{2\text{fertilizer}}$ index (Table II).

2) H_2O_{waste}: Given that the quantity of water required by cotton cultivation depends on the temperatures of the region in which it is cultivated and that the relation between average temperature and water required is unclear, the average water waste due to the most used type of irrigation in each country was considered. Thanks to a research of Wageningen University [7] different types of irrigation, the connected efficiency and the countries in which these are used the most have been identified:

- **Flood-or-furrow irrigation**: efficiency between 20% and 50%, 95% of irrigated cotton fields in India, Uzbekistan, China and some of the cultivation of United States.

[1] balanced fertilizer use, better management of crop residues and restrictions in pesticides application

TABLE III: Water efficiency

Country	Water efficiency	H_2O_{waste}
India	38%	0.23
Peru	39%	0.24
China	25%	0.06
Bangladesh	25%	0.06
USA	60%	0.52
Vietnam	28%	0.10
Italy	50%	0.38
Uzbekistan	21%	0.01
Turkey	40%	0.26
Egypt	35%	0.19

- **Mobile irrigation system**: efficiency around 80% - 90%, used in some American cultivation. It requires trees and other obstacles to be removed from the fields.
- **Drip irrigation**: efficiency between 90% - 98%, used in less than 1% of global cultivation.

An average water-waste per country was estimated and the obtained water efficiency was normalized in a range going for 1 to 0 from more to less sustainable (Table III). Below the formula used to calculate the H_2O_{waste} index:

$$H_2O_{\text{waste}} = 1 - \frac{100 - \text{efficiency} - 2}{80 - 2}$$

B. S_w - Workers conditions index

To model a good sustainability index, it was also considered the ethical side, so the one related to workers conditions.

Working with cotton is a long process [8] made up of various steps: the considered one is harvesting.

There are a lot of countries that do not have proper laws to guarantee people a good life: in many cases workers are treated as slaves, living in poverty and giving all their life to their job. Critical conditions can be found in countries like Bangladesh [9], Vietnam, Uzbekistan [10] and in some cases India [11].

There are a lot of factors that can be considered to properly model an index for workers: salary, benefits, work hours, vacation, presence of bonuses, age they begin to work, growth opportunities, cost of the life in proportion to their salary and security on work position. Unfortunately some of the considered countries in this project do not even provide information for factors related to benefits and good working characteristics, so for the index the used ones are:

- **Salary**: how much money does a person gain in a month. For cotton workers salaries are not high: the highest are the ones in the most civilized countries (USA, Italy, Egypt, Peru) where there are laws and regulations indicating the minimum wage. In other nations, like Bangladesh or Vietnam, information is barely known by the world organizations and therefore an estimate could just be made. Often people do not earn enough money to have personal effects, hobbies or even just internet connection and the possibility to travel by public vehicles.
- **Cost of life** [12]: an estimate of the money a person must spend to live – like for buying food, paying house

TABLE IV: Multiplier given by work hours.

Work hours	Multiplier
8	8
9	7
10	6
11	5
12	4
13	3
14	2
≥ 15	1

rent and bills - in a month. If on one hand civilized countries are the ones where salaries are higher, on the other they are obviously the ones where life costs the most. However, there are countries where salaries are very low and do not nearly cover the monthly cost of living. Often workers in these contexts try to work as much overtime as possible (in some cases mandatory, such as in India where there are 4 hours of mandatory overtime per week [13]), coming to work for a very long time in very poor conditions, without the possibility of eating and drinking properly.

- **Work hours**: how many time per day a person works. Connected to the previous point, leaving aside the more civilized countries, in many cases the working hours are a lot, the bonuses are few and there are no breaks or days off or leave.
- **Age**: it is important to consider also the age a person starts working, because ethically child exploitation is a big problem of some societies [14]. In some countries, children are forced to work since they are 14 years old, in other cases younger, but there are no official sources on which to base this. Children and women, especially in the textile industry, are exploited for their small hands and agility. Governments are fighting this problem: in some countries they succeeded, as in Turkey and in some parts of China, but often they do not know where to intervene, since it is all undeclared and often untraceable work.

Given those factors, the hardest job has been to properly put together all of them. The resulting index is then divided in 3 main sections:

- A relation between salary and cost of the life calculated for a month.
- A multiplier given by the work hours: the more hours a person works, the less is the value of the multiplier (Table IV).
- A penalty given to the beginning age: the youngest people starts working, the higher will be the penalty, calculated as a percentage (Table V).

In the end the resulting index is the following:

x = (salary / cost of life) * multiplier
S_w = x - (age percentage penalty of x)

Taking into consideration Table VI, it can be noticed how different the values for these countries are: Bangladesh has a low relationship between salary and cost of the life, people start working very young and work for many hours. In this case a multiplier equal to 4 is assigned and a percentage of 75% is applied as a penalty.

TABLE V: Penalty given by the age people starts working.

Age	Percentage
≥ 18	35%
16 - 17	55%
14 - 15	75%
< 14	85%

TABLE VI: An example of index calculation for 3 of the considered countries. Salary and cost of life are expressed in EUR/month.

Country	Salary	Cost of life	Working hours	Beginning age
Bangladesh	60	55	12	14
Egypt	115	55	8	15
Italy	1200	700	8	16

x = (salary / cost of life) * multiplier
x = (60 / 55) * 4 = 4.36
S_w = x - (age percentage penalty of x)
S_w = 4.36 - (75% of 4.36) = 1.09

C. S_t - Transport index

Transportation is the last essential category that has been considered in order to model the global sustainability index. Implementing an index that includes aspects such as energy consumption, load optimization, transportation costs, greenhouse gases and exhaust emissions allows to complete the general sustainability index adding an economic, environmental and logistical perspective on transportation. Similarly to the previous ones, the transportation index has to be modelled for all the ten countries under examination. However, differently from worker or production sustainability indexes, this index cannot be modeled merely gathering data from each country's internal transportation system. Since cotton is usually moved from an origin country to a destination one (that in many cases do not coincide) via road, maritime, air or rail transport, designing a network seems the best choice to model both such interactions between countries when transporting freight as well as the sustainability of the whole journey. Therefore, the adopted solution envisages the creation of a graph to model a simplified transportation system connecting countries by means of road, rail, air and maritime links. Afterwards, the embedded information in the graph's edges will be used to develop a metric that enables the sustainability calculation of the travel of cotton between countries assigning them this sustainability value.

The transportation graph (Figure 1) can be defined as a weighted graph $G = (N, E)$, where:

- N are the nodes, i.e. the list of ten countries for which S_{index} needs to be computed.
- E are the edges, i.e. the connections between countries, to which some attributes/properties are assigned.

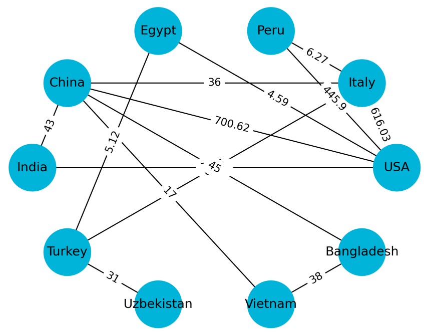

Fig. 1: Transportation graph

The whole graph has been built "ad-hoc", mainly due to the lack of free APIs and meaningful data dealing with sustainability in transportation. With the objective of making this simplified model more realistic, each of the links have been provided with some properties determined using the Emission Calculator from EcoTransIT [15], an online tool to perform calculations about transportation and environmental impact parameters (greenhouse gases, exhaust emissions and many more). The implemented properties in each of the edges are described below:

- **origin city**: the capital city of the origin country
- **destination city**: the capital city of the destination country
- **transport mode**: (*truck*, *sea_ship*, *train*, *airplane*)
- **freight** (tonnes): the carried amount of cargo (fixed to 100 tonnes for all routes)
- **load factor** (%): measures the effective utilization of the available capacity
- **distance** (km): distance between origin and destination countries
- **co2** (tonnes): amount of CO_2 emissions, an indicator of climate impact

Furthermore, the shortest path between each of the countries and a fixed destination country, i.e. the country where the goods need to arrive (Italy was chosen in this research), has been computed using the amount of CO_2 emissions as a weight. Indeed, the objective is to find paths with the lowest climate impact and use them to calculate the transport sustainability index S_t for each country with the formula:

$$S_t = \frac{\sum_{i=1}^{N} lf_i}{N \cdot 100}\left[S(\sum_{i=1}^{N}\frac{\mathrm{CO}_{2i}}{\mathrm{distance}_i}) - P(\sum_{i=1}^{N}\frac{\mathrm{cost}(tm_i)}{\mathrm{energy}(tm_i)})\right]$$

where N is the number of links in the path.
The index is mainly made up of two functions:

- the score function *S()* returns a rating based on the ratio between the total amount of CO_2 emitted during the travel (tonnes) and the total distance between countries (km), assigning scores according to Table VII and rewarding with higher scores those paths with fewer emissions compared to the distance travelled.
- the penalty function *P()* assigns a higher penalty to those transportation modes that have higher cost (€) in delivering one tonne-kilometer of freight [16] compared to the energy consumption (MJ) [17]. Penalties are reported in Table VIII.

TABLE VII: Transport scores

$x = \frac{\mathbf{CO_2}}{\mathbf{distance}}$	**Score**
$0 \le x < 0.0001$	10.0
$0.0001 \le x < 0.001$	8.5
$0.001 \le x < 0.01$	7.0
$0.01 \le x < 0.1$	5.0
$0.1 \le x < 1$	3.5
$x \ge 1$	0

TABLE VIII: Transport penalties

$x = \frac{\mathbf{cost}}{\mathbf{energy\_consumption}}$	**Penalty**
$x \ge 0.1$	0.1
$0.01 \le x < 0.1$	0.05
$0 \le x < 0.01$	0.01

Finally, the last step was to multiply the difference between *S()* and *P()* functions by the average load factor in the path: this choice aims at penalizing unexploited load capacities that may result in a subsequent increase in CO_2 emissions.

D. Multi-objective optimization

Given the sustainability problem defined so far it was decided to perform a multi-objective optimization aimed at minimizing the overall cost while maximizing cotton sustainability. The problem has been implemented as constrained, imposing penalties to prices that were not aligned to the sustainability level of the proposed solution. Prices have been defined looking at real data of cotton market and estimating a range that was able to describe the average global offer.

The country-specific indexes are not used in the optimization problem but are useful to compare the obtained Pareto front (Fig. 2) with the approximated cases.

III. Results

The first step in searching for an optimal Pareto front was to formulate a constrained optimization problem. The four variables employed to model it are:

- *price* (range [0.5, 5])
- *production index* (range [0.5, 10])
- *workers index* (range [0.5, 10])
- *transportation index* (range [0.5, 10])

Among those variables, price is the only one that has been minimized during optimization. All the other three, since they are related to the overall sustainability index that has to be maximized, have been maximized as well. The two fitness functions designed for the evaluation of price and sustainability objectives are defined including all these four variables. Then, NSGA-2 as a multi-objective optimization algorithm has been used to generate the Pareto front of non-dominated solutions, which is visible in Figure 2. After a fine-tuning of the algorithm's parameters, the following values have been finally set:

- **pop_size** = 100
- **max_generations** = 10
- **mutation_rate** = 0.1

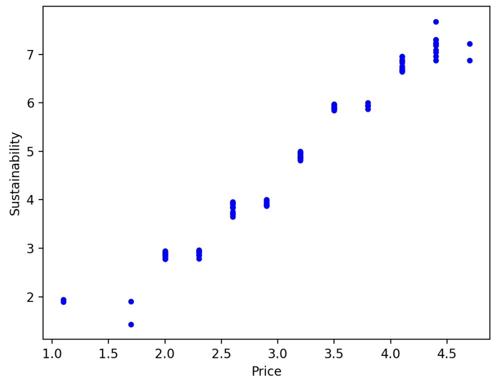

Fig. 2: Pareto Front

A high value for population size and a low mutation rate aim at shaping a Pareto front that is uniform and shifted towards optimal solutions. An initial test was done on an unconstrained version of the problem, without taking into account violations. In this situation, values in the Pareto front ranged in the highest sustainability values, i.e. around 9, and also in the lowest prices, i.e. around 0. However, in real-world scenarios it is almost impossible to have high sustainability being associated to a low cost. Usually, the more expensive the product, the more sustainable it is. Therefore, in order to avoid situations that cannot be realistic and to make the relationship between price and sustainability more coherent, some constraint violations have been introduced. Essentially, constraints enable sustainability values in a given range to have plausible prices. As a solution, violations have been set by subtracting values to the price so that it is more aligned with that sustainability range. The Pareto front that was finally generated includes solutions that might be considered a good trade off between sustainability and price, covering almost all possible values among these two objectives. By comparing the front with the sustainability indexes and prices assigned to the ten countries under examination, nearly all the countries are aligned (or a little below) to the values in the Pareto, meaning that the proposed trade off is feasible. Instead, it can be observed that some countries, such as Italy or USA, exhibit an optimal trade off that is even dominating with respect to the front, suggesting an infeasible solution since, as said previously, in most real cases a high sustainability is not often associated to a price that is too low.

IV. Conclusion

The theoretical problem definition behind this research enlightened a lack in data availability for the values referred to pollution caused by fashion: while the literature, as well as the audience, regarding this problem is board, it is clear that there is a lack of transparency on the real values of pollutant elements connected to fashion. Firms provide few details about their policies towards workers, especially when operating in countries with scarce regulations. It was also observed that in some countries there is a gap between the declared policies towards workers rights and the reality, as it can be assessed looking at data connected to unfortunate catastrophes or real salary values. For these reasons the whole research has been based on an approximation of the reality, using ranges of values defined coherently with the available data.

The problem of sustainability in fashion needs to be addressed reducing the global textile consumption, as the current levels of production are unfeasible and are impoverishing countries that already have a non-negligible low level of resources. Beside this aspect, it is clear that there are margins to improve the processes behind fashion production in several ways, focusing on the cultivation of natural fibers and growing them with a sustainable approach, preferring railways and maritime means of transport and reducing the number of trips always maximizing the load. At the same time there is the need to apply stronger regulations for the workers employed in the fashion supply chain, especially in countries that are absorbing the massive fashion demand of Europe and America.

The results obtained with NSGA-2 are interesting, as the individuals in the final population embed solutions that are quite similar to the values that were estimated for the 10 representative countries.

Valentina Sofia Pigato Curated the research and implementation of the Transportation Index S_t.

Amanda Asia Salvaterra Curated the research and implementation of the Workers Index S_w

Beatrice Marsili Curated the research and implementation of the Production Index S_p.

Team work The final index S_{index} has been defined collectively.
The multi-objective optimization problem has been formulated and implemented by all the participants.

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