From Innovation to Implications: A System Dynamics Analysis of Rebound Effects of Digital Textile Microfactories in the Fashion Industry

Luis Stütz[1], Juan Esteban Martinez-Jaramillo[1*] & Meike Tilebein[1,2]

[1] University of Stuttgart, Institute for Diversity Studies in Engineering, Pfaffenwaldring 9, 70569 Stuttgart, Germany

2 German Institutes of Textile and Fiber Research, Körschtalstr. 26, 73770 Denkendorf, Germany

**Corresponding author: Tel.: +49 711 685-60702; E-mail address: juan.martinez@ids.uni-stuttgart.de*

Abstract

Fashion is characterized by being a high-resource consumer, having globalized supply chains, and overproducing, leading to a high volume of waste and pollution. Hence, this industry needs to transition to one that is more environmentally friendly. One potential solution comes from Industry 4.0 in the form of Digital Textile Microfactories (DTMFs). DTMFs offers a customer-centric focus while digitalizing the design and production processes, resulting in environmental benefits. However, the lack of historical cases of DTMFs impedes understanding the potential impacts of DTMFs. This paper uses a System Dynamics approach to analyze the environmental impacts of introducing DTMFs. Our focus is to study the effects of shortened lead times, enhanced sustainability in production, and the potential price that DTMFs on consumption. Our results suggest that new digital technology in form of DTMFs alone is insufficient to mitigate the environmental impacts of the fashion industry. Therefore, in addition, a change in customer behavior is required to achieve a more sustainable fashion sector.

Keywords: Digital Textile Microfactories, Simulation, Rebound Effect, Archetypes, System Dynamics

1. Introduction

The fashion industry has rapidly grown, having an average increase in the annual production of 2% during the last decade (Gazzola et al., 2020). The main causes of this surge in production are the increase in population and the success of the fast fashion business model (Camargo et al., 2020). The main environmental impact of this success is the growth in CO_2 emissions. By the end of 2021, the emissions from the textile industry were estimated to be around 1.2 billion tons of CO_2 equivalent, which accounts for 5% of global emissions (Backs et al., 2021a; Pornsing et al., 2022). An additional environmental impact derived from fast fashion production methods is the increase in textile waste, calculated at 92 million tons for 2020, representing an additional burden on the environment (Centobelli et al., 2022; Chen et al., 2021). These adverse environmental impacts are not just a consequence of the volume and scale of this industry but are more related to the inherent characteristics of the fast fashion business model.

The fast fashion business model shows three characteristics, that contribute to its environmental footprint. Firstly, it relies on complex and extensive supply chains, resulting in high emissions due to the high volume of products transported along the whole supply chain (Backs et al., 2021b; Mehrjoo & Pasek, 2016). Secondly, the emphasis on mass production, while cost-effective, poses environmental challenges. Production is usually located in countries with lower salaries and raw material costs (Joy et al., 2012; Mihm, 2010), accompanied by less strict environmental and energy efficiency regulations (Williams, 2022). Thirdly, fast fashion has led to an increase in clothing consumption per capita through fast production cycles, low prices and weekly collections, resulting in shorter product life cycles, overproduction and increase in textile waste (Niinimäki et al., 2020).

The concept of Digital Textile Microfactories (DTMFs) emerges as a potential solution to mitigate the fashion industry's environmental impact. DTMFs apply new digital technologies, embodying digitally networked development and production processes for fashion (Wiegand & Wynn, 2023). DTMFs are characterized by a digital core that ensures high speed, efficiency, and quality in fashion production, along with close customer interaction (Tilebein, 2019). By adopting decentralized and local production concepts, DTMFs enable manufacturing near the point of sale or use, resulting in innovative, sustainable solutions that can shorten production times and have significantly more environmentally friendly production practices (Weiß et al., 2023; Winands et al., 2022). Hence, at a first look, DTMFs have the potential to significantly reduce in three ways the environmental impact produced by the fashion industry. Firstly, with digitalization, there is less need for physical samples in the design process, and secondly, DTMFs enable to apply small series and make-to-measure strategies, which reduce overproduction (Arfaiee et al., 2023). Finally, with better practices and localized production there is less CO_2 emissions associated with the supply chain (that spans from the raw materials until the final product is delivered to the customer).

However, despite the promising potential benefits of DTMFs as an innovative production concept, a need for more reliable empirical data currently hampers a comprehensive understanding of their potential impacts on the environment. Some counter-intuitive behavior can arise from the potential environmental improvements that DTMFs may have. One could think of the risk of potential rebound effects in which the initial improvement, given an increase in efficiency, can be overwhelmed by an increase in consumption intensity (Font Vivanco et al., 2022; Zerbino, 2022). While the resource- and emissions-saving attributes of DTMF production yield short-term reductions in emissions, the sustainable image, coupled with attractive pricing and the ability to provide increased customization to end-customers, could drive increased clothing consumption in the medium and long term. This could wipe out initial emissions savings and exacerbate environmental problems (Martinez-Jaramillo & Tilebein, upcoming).

This paper aims to answer the question of how short lead times, an increase in the sustainable image of the industry and competitive prices on DTMFs production could influence the fashion market and the environment. We focus this analysis on potential rebound effects that DTMFs can bring to the sustainable aspects of the fashion industry using the example of T-shirt production. To answer these questions, we developed a System Dynamics-based model with an aggregate view of the fashion industry. We use this simulation model to test scenarios that address uncertainties of changes of market conditions on potential environmental effects of the penetration of DTMFs. Overall, the motivation of this analysis is to be a tool for the decision-making process of policy makers and firms by enhancing the understanding of the underlying behavior given the structure of the system. Hence, this paper aims to contribute to the discussion of the potential impacts of DTMFs by providing insights from the perspective of system thinking to uncover unfavorable dynamics and effects in advance. This model quantifies monthly CO_2 emissions derived from DTMF and conventional T-shirt production. This calculation considers production volumes and the customers´ purchasing decisions.

The paper is organized as follows: In the next section we outline the background of the fashion industry. Section 3 exhibits the methodology and describes the simulation model, then Section 4 shows the scenarios, and the associated simulation runs. Section 5 discusses the results and finally we summarize and present the outlook of this paper.

2. The fashion industry: fast fashion vs. sustainable fashion

In the following subsections, we focus on three topics of the fashion industry and customer behavior that are relevant for this research. Section 2.1 presents facts concerning the phenomenon of fast fashion and its environmental impacts. Section 2.2 presents Digital Textile Microfactories (DTMFs) and discusses their potential to transform the textile industry. Lastly, Section 2.3 explores the main drivers that influence customer behavior towards sustainable fashion. We discuss how the encompassing psychological, socio-economic, and marketing dynamics can impact the purchasing decision. The purpose of section 2 is to understand the primary hypotheses of the simulation model and allow us to have a better understanding of the evolving dynamics within the fashion industry.

2.1 Fast fashion and related environmental impacts

Since the 1990s, the average annual rate of garment production increase has been estimated at 2%, and total garment production is projected to reach 102 million tons by 2030 (Lu et al., 2022; Niinimäki et al., 2020). The rise of fast fashion has driven this growth. This business model has changed the production dynamics of the fashion industry. Traditional Western manufacturers have slowly transitioned into purchasers while outsourcing labor-intensive activities to low-wage countries (Peters et al., 2021).

The success of fast fashion can be attributed to several factors. Globalization, economies of scale, and demand stimulation allow the fashion industry to expand its production supply chains and reach a broader customer base (Camargo et al., 2020; Gabrielli et al., 2013; Mihm, 2010). Other factors are technological developments, in particular social media and e-commerce. Both developments have created new marketing channels with more direct contact with the final customer (Peters et al., 2021). These strategies along with a shortened product life cycle of fashion trends and an increase in collections to 52 per year promote excessive consumption and short-term garment use, leading to impulse purchases by creating artificial demand (Kaplan et al., 2022; Niinimäki et al., 2020).

The current fast fashion model drives high production volumes, low quality, and distorted prices, negatively impacting the workforce, human rights, and the environment (Blesserholt, 2021; Joy et al., 2012; Williams, 2022). For instance, leading fast fashion brands generated around 92 million tons of textile waste in 2020, which is forecasted to arrive at 134 million tons by 2030 (Chen et al., 2021). Addressing these challenges requires a shift toward a non-wasteful and environmentally friendly economy (Moorhouse & Moorhouse, 2017). This is especially crucial in the EU; the European Green Deal aims to make the union climate-neutral by 2050. Being climate neutral includes reducing emissions, increasing renewables and efficiency, promoting sustainability, biodiversity, and a circular economy (Directorate-General for Communication, 2024).

The European Comission developed the EU textile strategy. This strategy encourages a transition towards a more environmentally sustainable and economically robust textile industry resilient to global disruptions (European Commission, 2022). The European Commission aims that for 2030, all textiles introduced into the EU marketplace embody durability, repairability, and recyclability, primarily derived from recycled fibers, devoid of harmful substances, and manufactured in adherence to social equity and environmental stewardship. Consequently, these goals can change the paradigm for the obsolescence of fast fashion, emphasizing prolonged consumer utility through access to affordable, high-quality textiles. The main policy areas are circular economy, sustainable production, waste shipment, textiles ecosystems, waste management, and recycling (European Commission, 2022).

To reach these goals, the European Technology Platform for the Future of Textiles and Clothing (Textile ETP) developed the Strategic Research and Innovation Agenda (Textile ETP, 2022). The second innovation theme claims research needs with regard to “Digitized textile materials, products, manufacturing, supply chains and business models”. Furthermore, this theme acknowledges that the textile manufacturing is undergoing a profound transformation. This theme seeks for: digital production creation (simulation, modelling and fully 3D prototyping), digital manufacturing and learning factories (digital microfactories, digital training tools, and digitized data-driven textile manufacturing environments), and digital supply chains and business models (digital data generation and digitally enabled service business models and sustainability) (Textile ETP, 2022).

2.2 Digital Textile Microfactories

Microfactories were first originated in Japan in the 1990s to deal with the downsizing of machine tools and manufacturing systems (Okazaki et al., 2004). Within the clothing industry, microfactories and digital textile printing are seen as a promising technology (Tilebein, 2019; Winands et al., 2022; Winkler et al., 2022). A Digital Textile Microfactory (DTMF) embraces a high degree of digitalization with short distances between production steps. Digitalization of the production process could bring firms benefits such as flexibility, efficiency, major control on quality, higher personalization of products with lot size one, decrease in waste, and the non-requirement of ramp-up processes (Artschwager et al., 2022; Weiß et al., 2023). Another benefit is that DTMFs shift manual, labor-intensive steps of traditional garment production to one that streamlines the process through 3D scanning, virtual try-ons, 3D design, and simulation, minimizing sample production and reducing costs (Shen, 2020). Other steps, such as cutting, printing, and assembly are guided by the 3D design and simulation, resulting in a finished product with precise measurements (for more details of the process please read (Arfaiee et al., 2023)), low waste, manual process requirements, and reduced developmental efforts (Artschwager et al., 2022).

DTMFs is a concept that could transform the current textile and clothing industry towards one that is resource-efficient production (Arfaiee et al., 2023). In contrast to fast fashion production methods, DTMF has the potential to significantly reduce the environmental impact through "on-demand" and "on-site" production strategies, made-to-order to current needs, minimizing surplus and returns. These combined strategies reduce the waste, overproduction, transportation distances, and emissions related to the development and production process (Arfaiee et al., 2023; Weiß et al., 2023).

2.3 Drivers for customers' behavior in sustainable fashion

The literature has extensively discussed the drivers that trigger the consumption of sustainable products in the fashion industry. For instance, Zheng and Chen (2020) identify the sustainable fashion environment, product features, and consumption awareness as key influencers on customers' consumption patterns. A range of factors have a direct impact on customer behavior. Rausch and Kopplin (2021) highlight the role of attitude, environmental knowledge, and concerns about greenwashing and economic risk. Other vital elements are customer attitudes, willingness to pay a premium, and the recognizability of ecological and social labels in driving sustainable clothing purchases (Busalim et al., 2022). However, sustainable products can also generate biases in the customers' choices. Two main effects can increase the demand for sustainable products in the short term: greenwashing and the green halo effect (Hameed et al., 2021).

2.3.1 Greenwashing

The term greenwashing involves prioritizing "green" advertising over actual eco-friendly practices (de Freitas Netto et al., 2020). Fast fashion companies often employ greenwashing to project sustainability without substantial improvements in their collections (Adamkiewicz et al., 2022). Many clothing companies use self-made eco-labels or certificates as a standard method for greenwashing. One has to add that there is a vast number of self-made labels (Stellmach et al., 2022). These labels are practical tools for gaining customer trust while reducing customers' feelings of guilt and thus encouraging them to continue consuming clothing in excess (Kaplan et al., 2022).

Firms have implemented "green" marketing campaigns as a competitive advantage as customers have become more aware of sustainability (Blesserholt, 2021; Lu et al., 2022). For instance, a study found that 70% of US customers are willing to pay more for environmentally friendly and fair textile products (PWC, 2021). However, customers face challenges in determining clothing sustainability due to limited information, extended supply chains, and transparency issues (Mizrachi & Tal, 2022).

2.3.2 Green halo effect

The halo effect was first described by Edward Thorndike (Greenwald & Banaji, 1995). The author argues that a person's qualities or work will be valued more highly if the general evaluation of that person is good. A preconception arises that attractive colleagues do better work simply because the general evaluation is higher based on the appearance of the attractive colleagues (Greenwald & Banaji, 1995). A reverse influence is also possible so that specific characteristics can influence the general evaluation (Cho & Kim, 2012).

The addition "green" comes when the tag of eco-friendly, fair, or sustainable is added to a product or process. It works the same way as the general halo effect: a more positive general evaluation of a product occurs due to evaluating a specific element, such as eco-labels. In the literature, this has been described mainly in connection with food (Lee et al., 2013), hybrid cars (Yao et al., 2023), and fashion (Zver & Vukasović, 2021). This effect positively influences customers' purchase decisions by increasing demand and the willingness to pay a surcharge.

3. Methodology

Currently, DTMF is in a development stage in which industry-scale labs exist and first application in industry are seen (i.e., Microfactory 4 Fashion coordinated by the German Institutes of Textile and Fiber Research (DITF Denkendorf, 2017)). However, this technology has not yet been widely commercialized due to uncertainties about the feasibility of new business models that come along the development of DTMFs and the potential risks and effects of this new technology (Winkler et al., 2022). However, DITF has been promoting DTMF on different textile fairs (being the last one TV TecStyle Visions in Stuttgart in 2020), showing to the textile industry the potential benefits of such set of technologies (DITF, 2020). Tilebein (2022) asserts the need to study the potential risks systematically. Additionally, the author recommends employing a systemic perspective to perform as first step a qualitative analysis of various archetypes that may initially emerge with the introduction of this technology and then in a subsequent step to have a quantitative approach using simulation (Martinez-Jaramillo & Tilebein, upcoming).

3.1 **Dynamic hypothesis: rebound effect and Digital Textile Microfactories**

The rebound effect occurs when the gains in efficiency or cost reductions derived from the more careful use of a resource incentivize its exploitation, thereby counteracting the originally intended conservation advantages (Brockway et al., 2021). This effect has been illustrated through system archetypes, as shown in figure 1. The fixes that fail archetype is a valuable tool that provides a framework to identify why a fix can increase the problem in the long term while, in the short term, there is a relief on the problem symptoms (Meadows, 1982; Senge, 1990). Essential elements to be considered are delays and feedback loops.

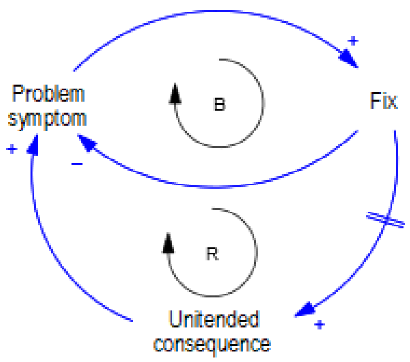


Figure 1. Fixes that fail archetype used to explain rebound effects

DTMFs concepts can increase efficiency and sustainability by promoting nearshoring and digitalization and providing made-to-measure garments that fit and do not have to be returned due to misfitting.

DTMFs enable local urban production with more eco-friendly supply chains than fast fashion (Arfaiee et al., 2023; Tilebein, 2019). Moreover, replacing conventional technologies by DTMF technologies could result in a substantial reduction in carbon footprint (Weiß et al., 2023). In addition, given the green deal´s goals, the European Union might foster the introduction of this new technologies as it has been done on other areas, e.g., solar energy, by subsidizing the consumption or the supply (Bertoldi, 2020).

Implementing DTMF technologies as a fix or mitigation measure to the environmental impacts produced by fast fashion may lead to counterintuitive dynamics, including rebound effects. Specifically, it is expected that substituting mass production of garments with DTMFs technology will result in a short-term reduction in emissions (recall section 2.2). However, this increase in short-term efficiency may lead to encouraging customer consumption of garments in the long term. Thus, DTMFs may potentially increase the garment demand and, with their nature of increasing customization, the pace of fashion. The reasons for rebound effects may result from customers perceiving DTMF garment production as more sustainable. This increase in the perception of sustainability could boost demand due to the greenwash effect and green halo effect, leading to more emissions than before implementing DTMFs.

Considering the uncertainty of the potential long-term impacts of DTMFs on the environment, we aim to build a quantitative analysis using simulation. The resulting simulation model allows us to have a holistic view of the mechanisms that can trigger rebound effects and also a way to prevent those from occurring or at least mitigate their effects. In the subsequent section, we describe the simulation model we developed, allowing us to study the implications of incorporating DTMFs in the fashion industry.

3.2 Model formulation

We developed a System Dynamics (SD) based simulation model, given that this methodology allows us to build a framework for modeling and simulating intricate systems. SD enables the identification of crucial variables and dependencies within a system (Sterman, 2000). This modeling tool proves adequate to integrate delays, feedbacks, accumulation processes of strategic resources, time delays, and non-linear interactions between the elements of complex systems (Cosenz & Noto, 2018; Morecroft, 2007). SD enables the examination of alternative scenarios (what if scenarios) and exploring the implications of various past and future assumptions (Sterman, 2002). Furthermore, the systemic perspective of SD allows to discover and analyze counter-intuitive effects in advance such as rebound effects. SD has found extensive application in studying rebound effects, addressing challenges like energy transitions, sustainable construction, regulation, or circular economy (Arias-Gaviria et al., 2021; Guzzo et al., 2023; Martínez-Jaramillo et al., 2023; Metic & Pigosso, 2022).

Our model takes a high-level view, using a monthly step to capture average patterns of fashion demand and supply of a German fictional city. This holistic view aims not only to asses DTMF production as a solution to the environmental problem of fast fashion but also to include the medium to long term impacts of such solution. It is imperative to acknowledge both apparent and indirect dependencies associated with the substitution of mass-produced garments by ones produced through DTMFs practices. This model quantifies the monthly CO2 emissions incurred during the production of garments within the clothing industry. We use as an example of garments a T-shirt, considering both the monthly production volume of DTMF and conventional reference T-shirts. The model is designed to simulate the purchase decision between a DTMF T-shirt and a reference T-shirt, accounting for various influencing factors such as sustainability image, price, average lead time, and environmental awareness of the population.

The simulation model was developed in Vensim DSS 9.3.5. The simulations run for ten years with a monthly step. We assume no improvement in technology efficiency on the traditional production or on DTMF technology. While we are aware of the increased pressure in European to reduce the environmental impact of all industrial sectors, it is not clear how the Europe Union will regulate imports of garments produced by fast fashion supply chains over the following years. Our aim is to understand how environment issues can encourage eco-friendly production alternatives and how these alternatives if not well planned can backfire the initial problem. Table 1 summarizes the data sources used to calibrate the model (base case) and the main assumptions.

Input	Data and hypotheses
DTMF and Traditional emissions per T-shirt	We assume an exogenous and constant value for emissions. DTMF: 2.88 kg CO_2-eq per T-shirt (Seibold et al., 2022) and Traditional: 3.29 kg CO_2-eq per T-shirt (Payet, 2021).
Initial DTMF and Traditional T-shirt price	We assume both prices are exogenous and constant (Seibold et al., 2022; Statista, 2023a). DTMF: 50€/T-shirt; Traditional : 20€/T-shirt
Monthly T-shirt purchases per person	We assume an exogenous and constant purchase of 0.25 T-shirts/month (Statista, 2023a).
Share of population pro sustainable products and population.	We assume an exogenous and constant share of 94% (KPMG, 2019). We assume a constant population of 100,000.
Overconsumption effect due to sustainability image	We assume an exogenous and constant value of 50%.
Initial lead time	Initial lead time of 180 minutes (Seibold et al., 2022).
Weighting factors for the purchase decision	Based on a survey we defined the weighting factors β1 (sustainable products), β2 (price) & β3 (lead time) (Statista, 2023b). These parameters are assumed constant. Other factors, such as fit, quality, appearance, or popularity of the fashion brand, were not considered due to the lack of comparability.
Learning curve and Experience curve parameters for lead time and DTMF price	We assumed constant values for the lead time (a rate of learning of 1% given the automatization of the process) and for the price (5% learning rate for the low manual labor participation on the production process) (NASA, 2007).
Average expenditure per potential customer	Fixed value: 40 Euros / person (Bodenheimer et al., 2022).
Monthly marketing allocation	We assumed a fixed allocation of 9% of the revenue.

Table 1. Data sources and assumptions for the base case

Figure 2 captures the stock and flow diagram that allows us to analyze the environmental impacts of introducing DTMF production. This diagram shows what are the causes and the effects using arrows to describe the relationships. This model can be divided in three main elements: learning curves (M1), the purchase decision (M2), and environmental impacts (M3).

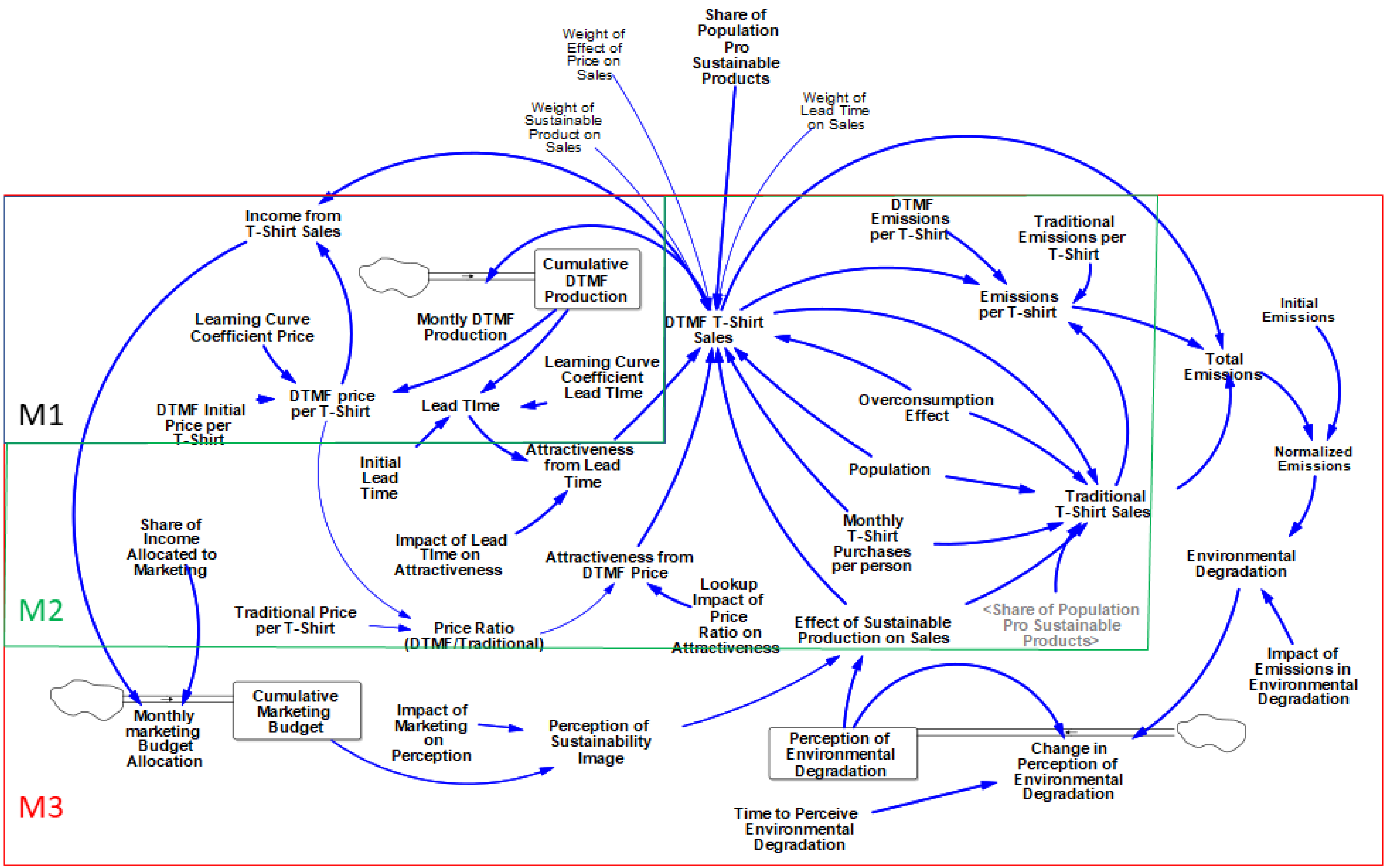


Figure 2. Full simulation model

3.2.1 Improvements in the efficiency of DTMFs-learning and experience curves

The first part of the model (M1) deals with modeling a DTMF T-shirt's price and lead time. For this purpose, the learning and experience curve is used, the core idea of which is that accumulating experience and information leads to improved performance, i.e. learning through application (Morrison, 2008). We include the learning and experience curve to model a decreasing rate using Equations 1 and 2.

$$LT = ILT * CDTMFP^{-0.990} \quad (1)$$

$$DTMFP = IDTMFP * CDTMFP^{-0.950} \quad (2)$$

The conventional form of the learning curve is a power function, which relates the currently required lead time or the current price (LT or DTMFP, respectively) to the initial lead time or the initial price (ILT or IDTMFP), the cumulative DTMF production (CDTMFP) and the learning curve coefficients. Both price and lead time are then converted into effects on the DFTMF sales using non-linear functions (please see Figures A1 and A2 on the appendix for the graphical representations) The lookup function for the attractiveness from the DTMF price (AP) has an inverted S-shape. The attractiveness from the DTMF price increases rapidly when the ratio between the price of DTMF and traditional is close to 1, given that more than 60% of German customers valued sustainable characteristics and at the same time are willing to pay a premium for green products (Statista, 2023b).

The lookup function for the attractiveness from the lead time (ALT) has a convex shape, capturing the perceived and effective waiting time on customers satisfaction. The lookup shows how customers satisfaction drops steeply when customers perceived that the service time is just surpassing their expected waiting time. Above a certain threshold, the perception of service will not be significantly affected by an increase in the waiting time (Djelassi et al., 2018).

3.2.2 The purchase decision

The purchase decision (M2) is the core of this simulation model and determines the DTMF T-shirt sales (DTMFTS) and the traditional T-shirt sales (TTS). The purchase decision for a DTMFTS is calculated using a fitted multiple linear regression, as shown in Equation 3. This equation is dependent on the population (Pop), the monthly T-shirt purchases per person (MTPP), the share of the population pro sustainable products (SPPSP), the attractiveness from the DTMF price (AP), the effects of the sustainable production on sales (ESP), the attractiveness from lead time (ALT), the overconsumption effect (OE) and the weighting factors (β1, β2 & β3).

$$DTMFTS = Pop * MTPP * SPPSP * (AP * \beta1 + ESP * \beta2 * OE + ALT * \beta3) \quad (3)$$

One key element in the purchase decision is the perception of the sustainable image that the customers have concerning DTMF products. This image is the product of the firm's cumulative marketing budget (CMB). Equation 4 shows the equation for CMB which accumulates the monthly marketing budget allocation (MMBA).

$$\frac{d(CMB)}{dt} = MMBA; \qquad CMB(0) = 0 \qquad (4)$$

CMB has an impact on the perception of the sustainability image of the product. This image is a non-linear relationship; its graphical representation is shown in the appendix (Figure A3). When the customers perceive a high environmental degradation of the DTMF T-shirts, they raise awareness of the sustainable production aspects among the population. This behavior is depicted in the model with the help of a lookup function that relates the marketing budget used to the population's perception. The lookup function has an S-curve shape. The initial phase of adoption of the DTMF production is slow because people need to be informed and take time to accept the new technology. Therefore, the costs for the acquisition of a new customer are initially significantly higher than the assumed average of 40 euros. Over time, the adoption rate will accelerate as the DTMF production method becomes better understood and known, leading to broader adoption (Ramadani et al., 2019). Through recommendations and public presence, the information spreads further, which significantly reduces marketing costs per customer. Ultimately, the market is saturated, and significantly more marketing budget needs to be invested to reach new customers. This leads to an increase in customer acquisition costs.

The overconsumption effect (OE) is examined case-by-case, as there are currently no quantitative figures on this phenomenon. The overconsumption effect combines the greenwashing, rebound, and green halo effect (Blesserholt, 2021; Hameed et al., 2021; Lu et al., 2022), stating that customers tend to purchase more sustainable products due to the sustainability image.

Equation (5) shows how the traditional T-shirt sales are calculated based on the DTMF T-shirt sales and adjusted for the overconsumption sales. This can be divided into two parts, first the total T-shirt sales without the overconsumption effect (Pop * MTPP). The second part calculates the number of DTMF T-shirts that are sold due to the overconsumption effect ($Pop * MTPP * SPPSP * ESP * \beta 2 * (OE - 1)$). Thus, the traditional T-shirt sales are equal to the total T-shirt sales without the overconsumption effect minus the difference between the DTMF T-shirt sales and the overconsumption of DTMF T-shirts.

$$TTS = Pop * MTPP - \Big(DTMFTS - \big(Pop * MTPP * SPPSP * ESP * \beta 2 * (OE - 1)\big)\Big) \qquad (5)$$

3.2.3 Environmental impacts on customer behavior

The third part of the model (M3) describes the behavior and effects of the sustainability image. Firstly; total emissions (E) are calculated using Equation 6. Both sales of T-shirts (DTMFTS and TTS) are multiplied by the DTMF emissions per T-shirt (DTMFE) and the traditional emissions per T-shirt (TE) respectively.

$$E = DTMFTS * DTMFE + TTS * TE \qquad (6)$$

These emissions are then normalized by dividing the initial value of emissions (NE). NE is then linked to a change in the environmental degradation rate, which customers will perceive. Environmental degradation (ED) is a non-linear relationship; its graphical representation is shown in the appendix (Figure A4). Equation 7 captures the perception of environmental degradation (PED) as the adaptation of the changes in the perception of environmental degradation (CPED).

$$\frac{d(PED)}{dt} = CPED; \qquad PED(0) = 0 \qquad (7)$$

An increase in environmental degradation is believed to trigger a higher and more positive effect of sustainable production on sales. On the other hand, if emissions fall, the effect of sustainable production on sales is weaker. This behavior can be explained by the fact that media attention can change quickly, thereby influencing the public perception of the urgency and need to change customer behavior.

We performed the traditional tests to validate SD models (Barlas, 1996; Barlas & Carpenter, 1990). These tests include dimensional consistency, extreme condition tests (to ensure model robustness), and structure logic tests. The model has successfully passed these tests and respects basic physics laws.

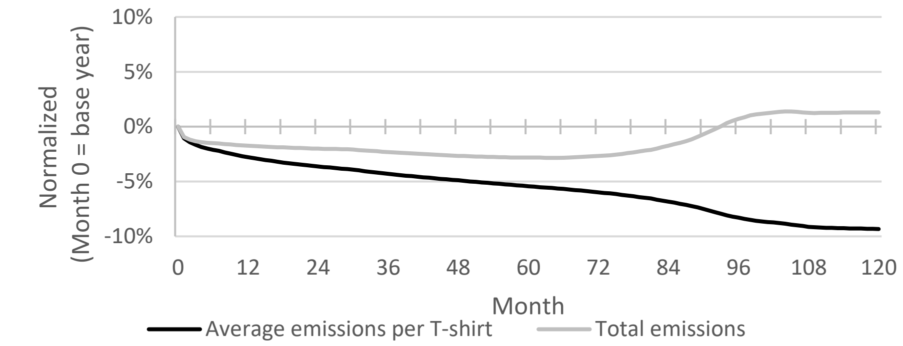
4. Results and analysis

We developed three scenarios which help us understand the dynamics behind the transitioning towards sustainable production (in this case DTMF). In the following subsection we explore the base case in which traditional firms do not use any competitive strategy against DTMFs nor DTMFs receiving subsidies from the government. Next, we run a sensitivity analysis to explore how robust are the results of the base case to changes in parameters. Finally, we explore two different market scenarios. First, we analyze the effect of competitive strategies (reduction in price) by the traditional firms. Second, we want to understand the impacts of subsidies to DTMFs. These scenarios were developed in order to have highlights of the environmental impacts on idealistic conditions (isolating different market conditions) but also under normal market conditions such as competition and market interventions from governments for new environmentally friendly technologies.

4.1 Base case scenario

We consider a base case scenario in which the main hypotheses are no competitive behavior from traditional firms (i.e., there is no change in price due to change in demand) nor governmental interventions (i.e., tax incentives or subsidies granted to DTMFs production). Fig. 3a shows the percentage difference in CO_2 emissions compared to the initial month. Recall that there are no improvements in technology efficiency, thus no increase in product sustainability over the simulation. We observe a rapid decrease in emissions during the first five years due to the gradual substitution of traditional T-shirts by DTMF production (the higher the share of DTMF production, the lower the average emissions per shirt sold). Although the average emissions continue falling during the following years, the total emissions start growing after the fifth year. This change in pattern accelerates in the seventh year, surpassing the initial emission levels. This shift in behavior is a consequence of the increasing volume of DTMF T-shirts sold (due to the overconsumption effect described in section 3.2.2), leading to a rise in the total demand, calculated to be 11.8% higher than the initial year (fig. 3b).

a. Percentual monthly change in emissions from T-shirt production



b. T-shirt sales per month (in thousands)

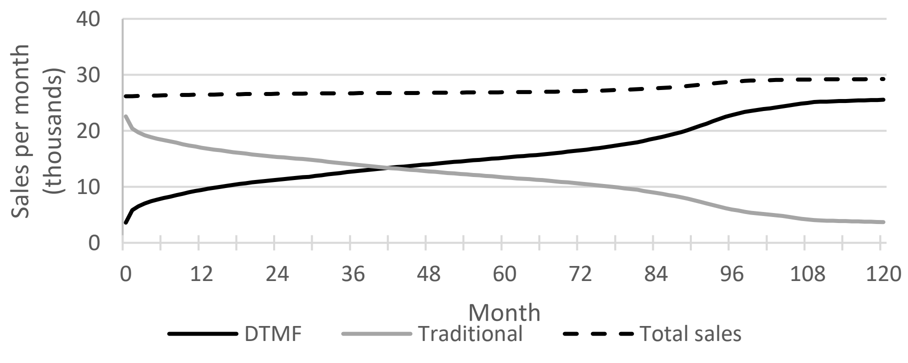


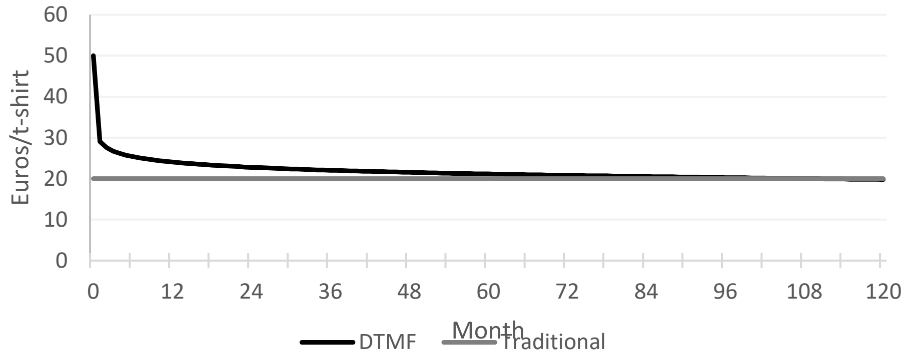
Figure 3. T-shirt sales and emissions in the base case

Figures 4a and 4b illustrate that price and customers´ perception of sustainability play a major role in explaining the dynamics of DTMF T-shirt sales. Although several factors can influence the customer´s purchase decision, the results suggest that price and the perception of sustainability significantly impact

DTMFs sales. On the one hand, price might be an important factor in the early adoption stage. The latter can be seen comparing figures 3b and 4a. Both figures show that a rapid reduction in DTMF T-shirt price encourages the adoption of DTMF, especially at the beginning of the simulation. These results seem consistent with the literature, which depicts price as a barrier to adopting sustainable products (Wiederhold & Martinez, 2018).

On the other hand, the customer´s perception of the sustainability image seems to significantly impact sales when the market is mature. The sustainable image becomes a major sales driver when price is no longer a barrier for adoption (see figures 3b and 4b after the 6th year), suggesting that customers then choose DTMF T-shirts given the intrinsic sustainable characteristics of DTMF processes. These results match those observed in earlier studies (i.e., Soyer & Dittrich, 2021; Wiederhold & Martinez, 2018) in which customers are attracted to products that focus on specific sustainable attributes, that adopt an efficient communication strategy and that make a great effort to make the apparel attainable.

a. Price per T-shirt DTMF vs. Traditional



b. Customers´ perception of sustainability image of DTMFs

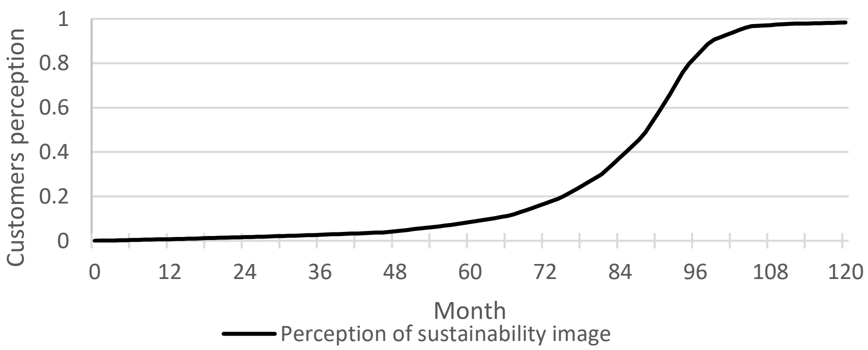


Figure 4. Factors for customers´ purchase decision

4.2 Sensitivity analysis

We test the impact of key parameters such as the learning curve coefficient for DTMF price per T-shirt, the share of the population against sustainable products, the overconsumption effect, and the population. These parameters were assumed constant over the simulation horizon. However, we acknowledge that, in reality, these are likely to change. We run a sensitivity analysis over the parameters shown in Table 2 to test how robust our model results are. For instance, " ±10%" means that this parameter is increased/decreased by 10% compared with the base case.

Parameter	Name	Change
Learning curve coefficient price	L^+, L^-	±10%
Share of the population against sustainable products	S^+, S^-	±5%
Overconsumption effect	O^+, O^-	±20%
Population	$P^{0.01}$,	+0.01%/year,
	$P^{-0.02}$	+0.02%/year

Table 2. Sensitivity analysis parameters

We use as metric the normalized emissions. We normalized the emissions using the initial emission value. This variable allows us to compare and understand the individual impact of these four parameters on the model behavior. For instance, a normalized value lower or higher than one means that emissions have decreased or increased, respectively, compared with the initial situation. For example, a value of 0.83 means that emissions decrease by 17% compared with the initial value. Figure 5 illustrates the outputs of our sensitivity analyses. Our results suggest that our model is robust to changes in these parameters and that our structure is consistent with our hypotheses, given that the behavior of all sensitivity scenarios shows a rebound effect. In almost all cases, emissions arrive at higher values than at the start of the simulation, except for O-. In this particular scenario, the normalized emissions are lower than one. However, the evolution of the normalized emissions shows also a rebound behavior (see figure 5c). The lowest value in O- is reached around the sixth year and after that emissions start to grow again. From our sensitivity analysis, we can infer that customers with a high focus on sustainability can produce unintended environmental consequences.

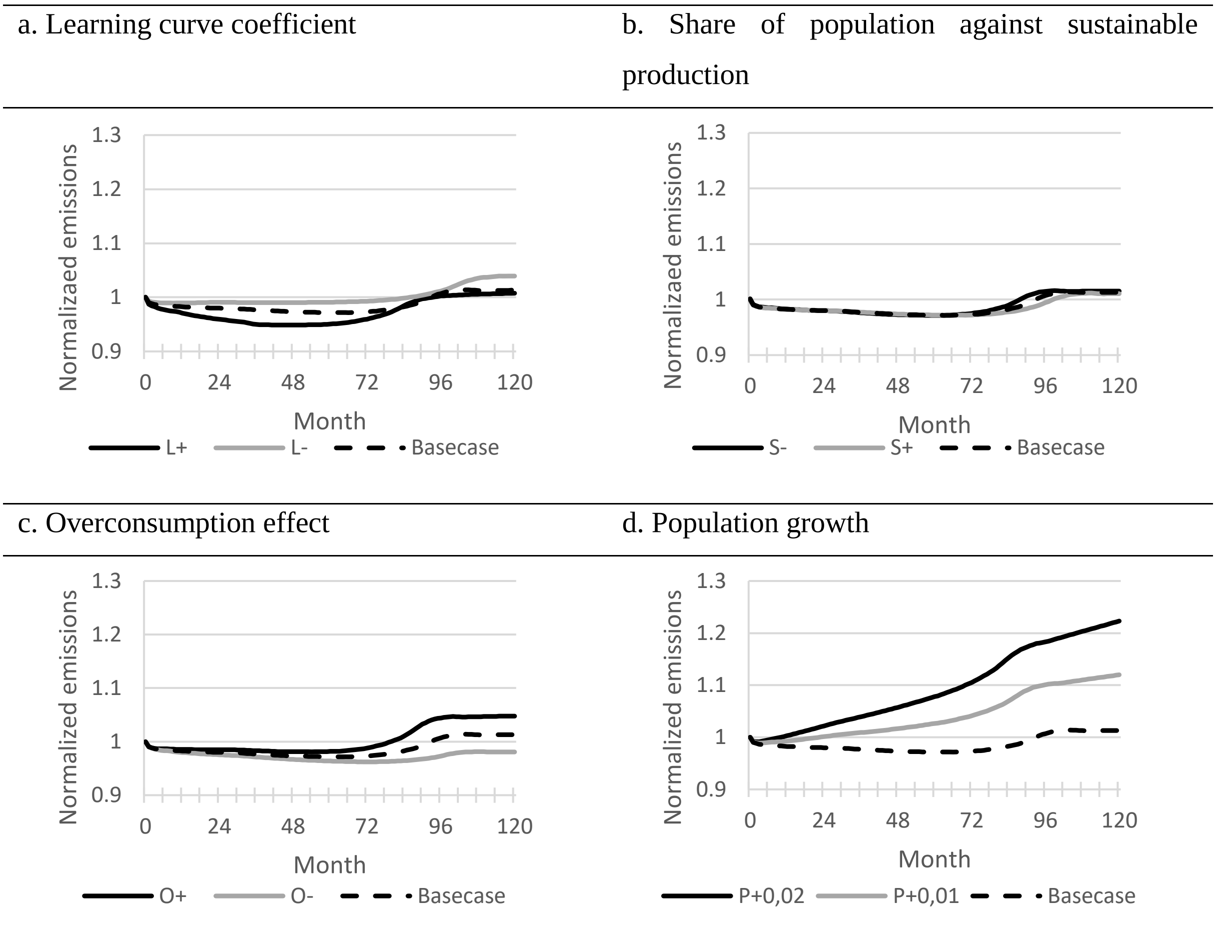


Figure 5. Sensitivity analysis results

4.3 Competition scenario

The previous analysis assumes that the traditional firms will not react to the penetration of DTMFs and later dominance of the market. In reality, decision makers of traditional firms will adapt their strategies to compete and also to try to remain relevant on the market. We are aware that companies compete using all of their competitive advantages (i.e., quality, brand awareness, service to the customer and price), though for this first experiment we assume that they will compete by reducing the unitary price only. Table 3 summarizes the changes for the competition scenario (C).

Variable/Constant	Equation
Price per traditional T-shirt	Initial traditional price-Initial traditional price *effect of competition on price
Effect of competition on price	Non-linear function of the ratio of the market share - Current/Goal (Figure A5)
Threshold	Traditional share of the market/Goal of share
Goal of share	Is a constant and defined in 50%

Table 3. Overview of model modifications compared to the base case scenario

Figure 6 shows the evolution of the price ratio. The price ratio determines how much more expensive a DTMF T-shirt is compared to a traditional one (one means that the price are equal, higher than one means that the DTMF shirts are more expensive and vice versa). This figure displays how traditional production adapts its price in an attempt to compete with DTMFs. In both scenarios, the price ratio rapidly falls as DTMFs become more efficient (learning curves), distributing the total costs on a higher production volume. Unlike the base case, C never faces a ratio equal to or lower than one. Moreover, while the ratio on the base case is always decreasing, the ratio on the C scenario arrives at its minimum value around the 90th month, from which the price ratio starts increasing again.

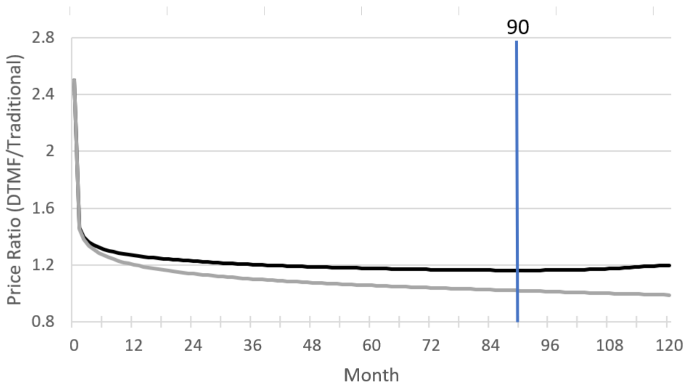
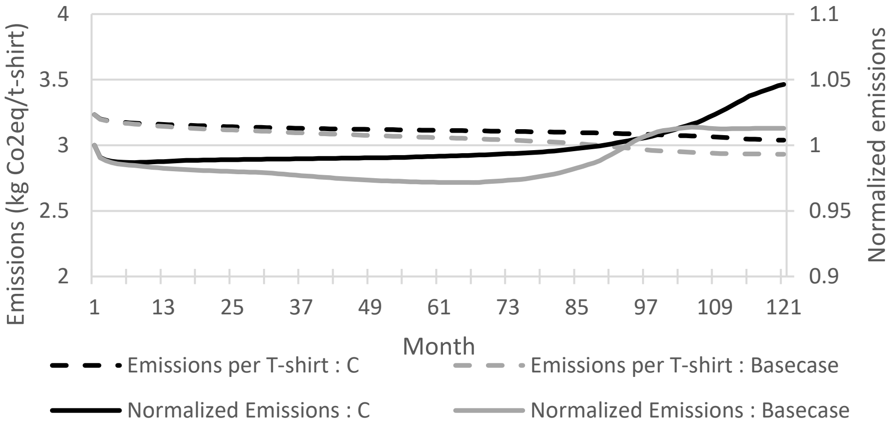


Figure 6. Price ratio by scenario

Figure 7a shows the evolution of the normalized emissions and the average emissions per T-shirt. As expected, with competition, traditional firms will try to stay relevant in the market, decreasing their prices and thus encouraging demand for their products. Figure 7b captures the purchasing behavior. It is unsurprising that the traditional sales are higher in the C scenario than in the base case. Furthermore, there is more demand for the traditional T-shirt, so there are more average emissions per T-shirt. The C scenario would be more realistic than the base case. However, a commercial war based on price will result only in having worse environmental impacts; the only winner will be customers as they can increase their purchases. Furthermore, a price war cannot be sustained for either competitor in the long run.

a. Normalized emissions from T-shirt production



b. T-shirt sales per month (in thousands)

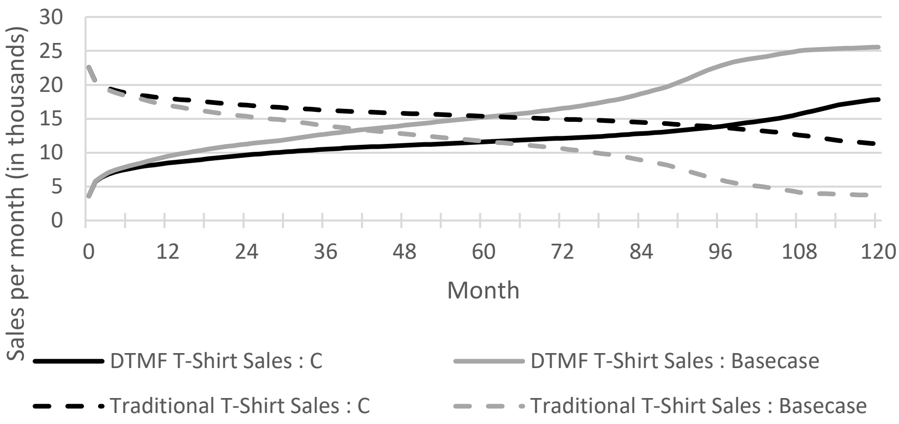


Figure 7. T-shirt sales and emissions by scenario

4.4 Subsidies scenario

The previous analysis has illustrated how competition can exacerbate the environmental problem. The results suggest that price is still a significant driver for the customer´s choice, so we next explore a mechanism on the supply side as an experiment. We propose a subsidy scenario (S) to reduce the initial DTMF price per T-shirt. The logic behind this mechanism is to encourage the initial adopters and thus accelerate the adoption process of DTMFs. This mechanism can be implemented in different ways. For instance, one could think of a VAT exemption for this product or tax relief for the producer. We assume that the initial price for a DTMF T-shirt can be reduced to 40 Euros (a 20% reduction). Figure 8 captures the impact of subsidizing DTMF T-shirts on the normalized emissions. While this scenario exemplifies the potential gains of a behavioral change, it also illustrates that those gains have only a relatively limited impact in the short term. As discussed in the previous scenarios, an increase in the efficiency of the emissions will lead to a rebound effect. In other words, the increased demand for garments from lower prices and increased sustainable image overwhelms the initial gains.

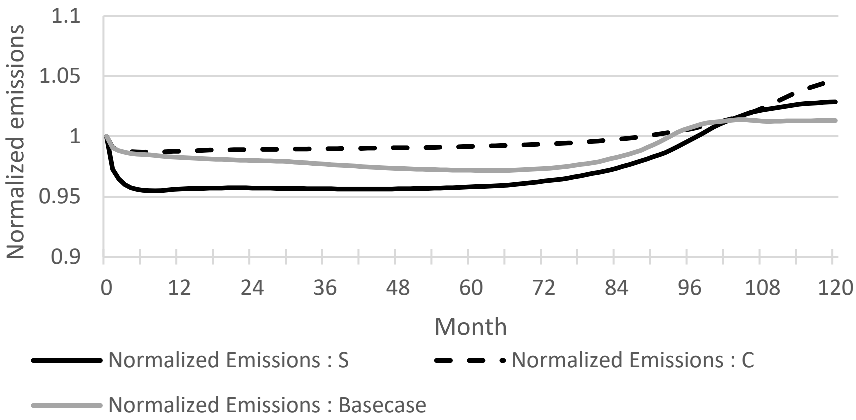


Figure 8. Normalized emissions by scenario

5. Discussion and conclusions

Our results suggest that introducing DTMFs in the fashion industry leads to a phenomenon called rebound effects. This effect has been explained in system thinking using the archetype "fixes that fail". DTMFs are thought as a potential alternative to mitigate the environmental impacts derived from the traditional production method. Theoretically, DTMFs have intrinsic characteristics that make this technology become a relevant actor in the fashion industry. On the one hand, DTMF has a lower environmental footprint.

On the other hand, DTMFs have short lead times, a higher sustainable image, and the potential to compete with prices in the long term with traditional production methods. These features make DTMFs a potential game changer in the fashion industry. DTMFs could be encouraged by local governments seeking to achieve emissions targets as they are perceived to have a lower carbon footprint than traditional technologies. However, this eco-friendly image, combined with the shorter lead times offered by DTMFs, can accelerate the pace of fashion. Furthermore, DTMFs potential to compete with traditional firms in terms of pricing makes this new technology an attractive alternative in the medium term for cost-conscious customers.

Given the hypothesis that DTMFs can further deteriorate the current environmental situation, we tested three scenarios. All simulations showed that the initial environmental benefits of DTMFs are over compensated in the long term. Demand increases because customers are attracted to buying even more fashionable garments (overconsumption) use due to their perception of being eco-friendlier. Our results should be seen as an experiment to gain knowledge of the dynamics resulting from innovations in the textile industry.

Our stylized model shows that the two main factors considered in the decision to purchase have different weights depending on which stage is the product life cycle. The S scenario suggested that during the introduction stage, price is the driver with a higher impact on adopting DTMFs. Between the growth and maturity stages, the sustainable image of DTMF becomes the most critical driver for the decision process. This is not surprising as during this phase, there is not a significant difference in prices between the traditional and DTMF.

Our results show some positive insights. We found that there was no rebound effect on the O- case. This result hints that accomplishing a low overconsumption effect can positively impact the environment. There are three main recommendations that can help to achieve a change on the overconsumption effect. Firstly, a strong marketing campaign focusing on the made-to-measure aspects of DTMF production could make people value their garments more. Secondly, public policies that aim to change consumption education concerning fashion. Thirdly, it is essential to inform the population of the advantages of DTMFs, especially in the early stages, and that this improvement could be sustained over time only if there is no overconsumption. While this study provides valuable insights, we acknowledge its limitations. We use a very generic analysis. Our research does not consider different DTMF technologies, market segments, or possible regulations, which may impact the results. We have a narrow system boundary that consider only production, thus if we include elements such as return rates we could expect higher emissions accounting for mass production in contrast to made measure garments, resulting in DTMFs production being even more sustainable. It is essential to keep in mind that this model has some simplifications. The most important one is to reduce the complexity of the purchase decision. We are aware that the purchasing decision depends on multiple factors that were not included, such as fit, quality, appearance, and brand reputation. Additionally, the model has strong assumptions. For instance, we assumed a constant population, as we wanted to isolate the demand changes by the greenwashing and green halo effect. We also did not consider dynamic changes in the customers' preferences or include technological improvements, as these factors were outside the scope of our research. Other environmental awareness factors go beyond pure emissions, such as public acceptance, political will, and customers' economic situation. Hence, this study gives first insights and point to potential counter-intuitive effects, more research is needed to supports policy recommendations.

6. Summary and outlook

In this paper, we develop an SD-based model to analyze potential impacts of introducing DTMFs on the environment. This model includes three main elements: the customer's decision process, a learning curve for the DTMF production process, and emissions. The decision rule includes three main drivers that were identified in the literature: price, lead time, and their customers´ perception of sustainability. The purpose is to observe the substitution of T-shirts purchased from traditional production towards DTMFs. Next, the model allows us to estimate the resulting emissions. Thus, our modeling framework allows us to foresee potential unintended consequences, particularly rebound effects. DTMFs are seen as a potential alternative to mitigate the environmental impacts of fast fashion. Nevertheless, our findings suggest that the initial emission reductions resulting from substituting production methods can become a more significant environmental problem in the long run.

We examined three scenarios: a baseline scenario with static competitors, a competitive scenario that introduces a dynamic pricing strategy on the side of the incumbent firms, and a subsidy scenario that incorporates price support for T-shirts produced using sustainable DTMF. The base case is used for comparison. In the competitive scenario, we include a more realistic response from the traditional firms. This scenario explores the influence of competition on the adoption of DTMF technologies. Lastly, the subsidy scenario explores a policy that can boost the initial adoption of DTMFs by price support of T-shirts. This scenario hints at the impact of public policy on the transition to sustainable production technologies. Furthermore, all three scenarios provide insights into different paths and challenges that can happen during the adoption of DTMFs and their implications on the textile industry and its associated carbon footprint.

Across all scenarios, the transition to an eco-friendlier production may result in a counter-intuitive increase in emissions over the long term. These results are consequence of an increase on the overall consumption due to the well-documented psychological phenomena that occur in the customer's choice process: greenwash, and green halo effects. Our analysis is useful to uncover different phases in the behavior. Our scenarios show that if customers change their behavior at early stages, there is a huge potential gain in terms of sustainability. However, these gains must be accompanied by policies that can maintain the level of consumption on the longerm. This highlights the need for a systemic approach to understand the causes and consequences.

In summary, it can be stated that sustainable production methods such as DTMFs can lead to rebound effects. Combining a sustainable image and an attractive price can influence clothing consumption and thus significantly limit the actual sustainability of the DTMF. The model shows that more sustainable clothing production alone cannot solve the environmental problems of the clothing industry. Consequently, the contributions of this paper are twofold: Our quantitative analysis provides insights for both decision-making in industry and for further research. Moreover, stakeholders should consider these findings when designing initiatives to promote sustainable manufacturing practices and address the environmental implications of fast fashion. Similarly, this research contributes to the field of System Dynamics by adding one real case in which the fixes that fail archetype can be used to explain the dynamics of DTMFs.

A possible focus of future research could be to extend this model to include other sustainable strategies such as clothing rental, circular economy, or resale of clothing via second-hand platforms. These emerging trends are possible approaches to reducing the consumption and production of new clothing. However, these strategies could be could also have counter-intuitive effects. In addition, it could be investigated how customers' consumption behavior can be influenced in order to limit overconsumption. Particular attention could be paid to providing customer information and education.

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Appendix - Graphical representation of nonlinear functional relationships.

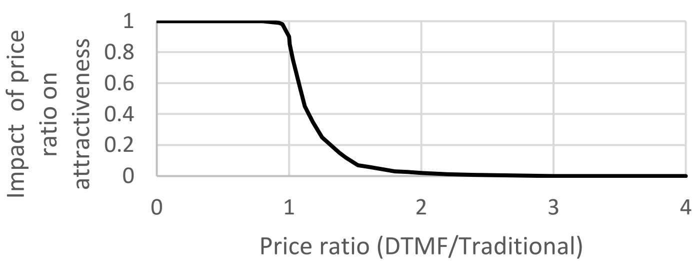

Figure A1. Impact of the price ratio on the attractiveness of DTMFs T-shirts

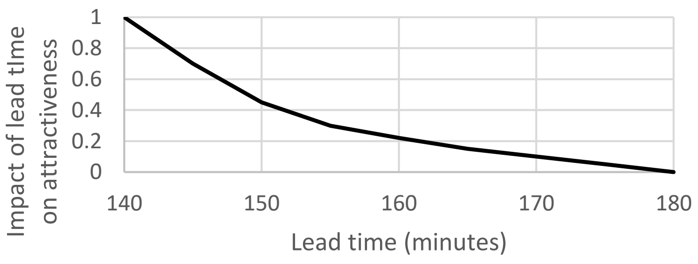

Figure A2. Impact of the lead time on the attractiveness of DTMFs T-shirts

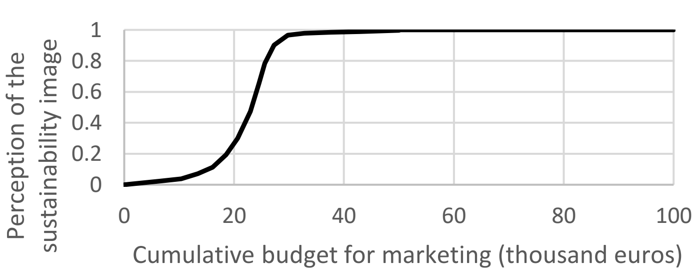

Figure A3. Impact of the cumulative marketing budget on the perception of the sustainable image

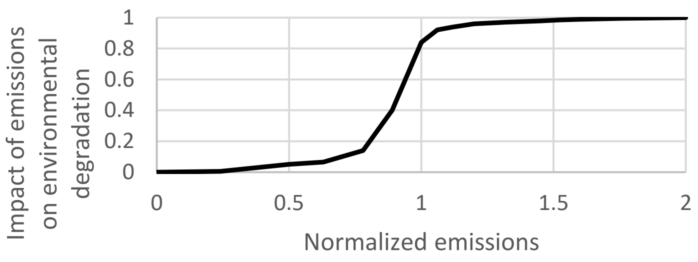

Figure A4. Impact of emissions on environmental degradation

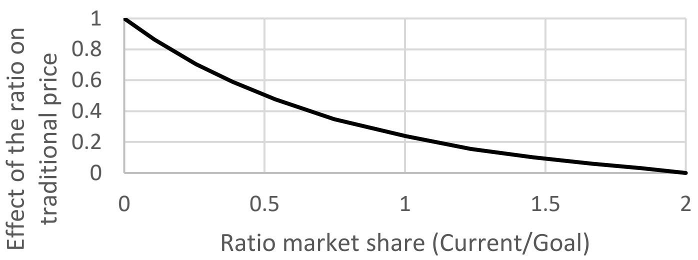

Figure A5. Impact of the ratio on traditional price