Modeling the impact of environmental consciousness on the supply-demand relationship between firms and customers

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Acknowledgments

The authors thank Prof. Robert Finger, Prof. Michael Stauffacher and Dr. Paolo Gabrielli for exchanging ideas on an early draft of this work and for suggesting on how to embed the research in the existing literature.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Names removed for double blind review

Abstract

An increasing environmental consciousness of customers can become a strong incentive for firms to supply environmental-friendly products. If these products are not available, supply-demand deficits emerge. We use an agent-based model with an underlying network topology to study different scenarios for mitigating these deficits. Both customers and firms can adjust their tolerance level for environmental pollution, but customers can also establish new relations with other suppliers, following different rules. We show that the optimal mitigation of deficits results if customers form unconditional supply links that may become effective in the future, while firms steadily improve their environmental-friendly production. Our findings can inform policies to reduce both supply-demand deficits and environmental pollution by increasing environmental consciousness.
Keywords: *environmental consciousness, supply and demand, economic networks, agent-based modeling*

Research highlights

- We investigate environmental consciousness as a behavioral opportunity for sustainable transition.
- We operationalize environmental consciousness in a formal feedback model.
- We model customer-firm relations and their dynamics by combining network and agent-based models.
- We study the emergence of local supply-demand deficits in customer-firm relations.
- We highlight how environmental consciousness increases these deficits and propose mitigation scenarios.

1 Introduction

Environmental consciousness can be defined as the level that an individual or an organization care about environmental issues [1], such as climate change. The latter has become one of the most important global problems since the end of 20th century [2]. More than 130 nations have already proposed net-zero carbon emission targets to keep the increase of global temperature below 2.0° [3]. To meet this target before 2050 [4] manufacturing industries are under pressure as they contribute a large share of the global carbon emissions [5]. For example, in 2019, more than 50% of China's carbon emissions came from manufacturing industries [6].

Customers' increasing environmental consciousness can become an important reason for manufacturing firms to reduce carbon emissions if customers start buying only "green" products from low carbon-emitting firms [7–10]. To not lose these customers firms need to improve their production process [11, 12]. As a first step, this requires an organizational learning process for firms to realize the impact of their production process on the environment [13, 14]. Understanding the environmental concerns of their customers may raise firms' own environmental consciousness [15] and lead to innovations in their manufacturing processes.

This idealized improvement scenario is counterbalanced by a number of economic constraints, most notably on the availability of products. The mentioned adjustments of firms take time to be implemented, so the supply of certain grades of products may be hampered. Further, producing environmentally friendly products comes with higher costs on the side of the manufacturing firms and the customers, so both supply and demand may drop down.

Therefore the implicit assumptions that customers with increasing environmental consciousness can always satisfy their demand for "green" products and that firms with the respective products can always supply their customers are not realistic. There may be shortages because supply exceeds demand, but also because demand exceeds supply. It is precisely this mismatch between supply and demand that motivates our publication.

Instead of a data-driven approach, we solely focus on *modeling* the dynamics by means of an agent-based model. This allows to study the feedback processes between customers and firms in more detail, using only a few reasonable assumptions. Yet, our guiding question, which scenarios are best suited to reduce supply-demand deficits, is of practical relevance. We will discuss in Section 6, how the optimal parameters and interaction rules can inform policies.

Agent-based modeling is widely used in the social sciences as a methodology to study the interactions of heterogeneous agents, as we detail in Section 2.1. We apply it here to *model* our key variable, the environmental consciousness of customers and firms. Environmental consciousness has already been measured in surveys and discussed with respect to brand marketing, manufacturing, or education

[1, 15–19]. But it was not used in formal models to understand the feedback on supply and demand mismatch. The supply-demand problem is usually addressed in economics by means of market models [20], with a focus on the role of prices and the efficiency of markets [21, 22]. Our model instead studies the emergence of *local* supply-demand mismatch even in cases where supply and demand are *globally* balanced. We discuss the impact of environmental consciousness of both customers and firms on the emergence of such a potential mismatch. Also, we explain the role of fixed versus flexible supply relations between customers and firms.

Our paper is organized as follows: After pointing out the importance of agent-based modeling in Section 2.1, we introduce the details of our method in Sections 2.2, 2.3. The model proposed there will serve as a reference case to simulate different scenarios for mitigating supply-demand deficits in Sections 3.1, 3.2. The results presented in Sections 4.1, 4.2 provide optimal parameters and rules to reduce supply-demand deficits and inequalities of customers satisfaction. After discussing our findings in Section 5, we provide insights for policy design and roll out possible extensions of our model in Section 6.

2 Methods

2.1 Agent-based modeling

In contrast to standard market models that match supply and demand using a market clearing mechanism, the focus of our investigation is the *heterogeneity* of customers and firms. Individual differences in supply of firms and demand of customers play a major role in our model, together with the fact that not all suppliers can serve all customers. Hence, customers and firms are also heterogeneous with respect to their *interactions*, i.e., their supply-demand relations.

Agent-based modeling seems to us the most appropriate methodology to reflect these various individual differences. The underlying interaction structure is captured in a network model where links represent the supply-demand relations and nodes the respective agents, i.e. the customers and firms. These agents are characterized by internal variables that can change in time together with their supply-demand relations. Hence, the agent-based model implements, in addition to the heterogeneity, a *feedback* between agents and their interactions, which makes it advantageous over other modeling approaches, notably system dynamics models [23, 24].

These advantages have made agent-based models the dominating approach to study complex adaptive systems, i.e. systems comprising a large number of interacting elements denoted as agents in the following. The aim of agent-based modeling is to explain system dynamics at the macro level *bottom-up*, i.e. starting from the properties and interactions of agents. Social and economic systems are prime examples for complex adaptive systems, hence, starting from the early 1990's numerous agent-based models have been developed to understand their structure and dynamics [25, 26]. One focus is on explaining collective behavior, ranging from opinion formation [27, 28] to the adoption of products and technologies [29, 30], the other one is on adaptation and learning[31]. The latter is of relevance to us because we want to study how customers *and* firms adapt their environmental consciousness to mitigate supply-demand deficits.

Existing agent-based models mainly focused on the behavior of customers, only. For instance, [32] used agent-based modeling to study consumers' adoption behavior for biomass fuel in Austria. They found that customers in relatively small regions adopt biomass fuel at a higher speed due to a higher communication frequency. [30] investigated customers' decision processes in accepting low-emitted heating systems in Norway. They concluded that heating systems' functional reliability is the key factor for customers' adoption decisions. [33] studied the mechanisms that influence the adoption of environmental-friendly vehicles. They argued that technology push and word-of-mouth effect can increase the adoption speed of environmental-friendly vehicles among customers.

We will extend such approaches by including the perspective of the manufacturers, i.e. we model *bipartite relations* between customers and firms. The mentioned studies neglected the supply side and implicitly assumed that products, like environmental-friendly fuel, heating systems or vehicles, are sufficiently available, to only focus on the adoption process of customers. In contrast, our model will include supply and demand deficits as a main feature. Eventually, instead of *external* economic or technological factors, we consider an *internal* factor, environmental consciousness, as a driver for customers' decisions. This bears the challenge to operationalize such a variable, for which we propose a solution.

Our model shares some general principles of agent-based modeling. The different scenarios we propose to mitigate supply-demand deficits neither assume centralized control, nor central optimization. This makes our approach different from, e.g., mechanism design where an optimal match between firms and customers is obtained algorithmically [34]. Instead, in our model firms and customers are seen as autonomous agents that make their decisions independently based on time-bound information. As a consequence, we observe the emergence of suboptimal supply-demand relations that seem to be useless for the aim of reducing deficits. However, what is considered a "deterioration" from the perspective of a social planner, later turns out to be the seed for an improved solution. This kind of evolutionary dynamics is very typical for self-organizing agent-based models.

2.2 Modeling supply and demand

In the following, we are more specific about the methods used. Our model considers N agents of two types: *customers*, $i = 1, ..., N_c$, and *firms*, $K = 1, ..., N_f$. To ease the visualization of our simulations, we have chosen $N = 50$, $N_c = 45$ and $N_f = 5$. All firms supply the same product and all customers have a demand for the same product, albeit at different quantities. Differences between firms result from the environmental impact in manufacturing their product, which is specified further in Section 2.3.

The actual demand d_i of customer i is fixed, but differs across customers. We sample it from a normal distribution $d_i \sim \mathcal{N}\left(\langle d \rangle, \sigma_d^2\right)$ with mean value $\langle d \rangle = 1$ and variance $\sigma_d^2 = 0.05$. The total demand is then defined as $D = \sum_i d_i \approx N_c \langle d \rangle$. Likewise, the actual supply s_K of firm K is also fixed, but differs across firms, sampled from a normal distribution $s_K \sim \mathcal{N}\left(\langle s \rangle, \sigma_p^2\right)$ with mean value $\langle s \rangle$ and variance $\sigma_s^2 = 0.05$. The total supply is then given as $S = \sum_K s_K \approx N_f \langle s \rangle$. Throughout this paper, we always consider equal mean values, $\langle S \rangle = \langle D \rangle$, i.e. on average there is a *global balance between supply and demand*. This defines $\langle s \rangle$ for given $\langle d \rangle$. The global balance makes it possible that, in principle, every customer could satisfy its demand and every firm could sell its production if customers and firms match correctly.

In our model, however, customers are only supplied by specific firms. These supply-demand relations are captured in the network shown in Figure 1a. The five firms in the center are linked to a number of customers in the periphery. The number of links, i.e. the *degree* k of firms and customers, are sampled from a broad degree distribution [35]. $P(k) = k^{-\kappa_1} \cdot e^{-\kappa_2 \cdot k}$ describes a power-law with an exponential cutoff, which is most suited to capture the *heterogeneity* in the number of relations. We have generated the degree sequence of all agents from the degree distribution with $\kappa_1 = 2.1$, and $\kappa_2 = 0.004$. In the resulting network, customers are represented by nodes with a degree $k_i \leq 10$. The few nodes with $k_K > 10$ represent firms. Hence, firms supply many customers, while customers obtain products only from a few firms.

Because links between agents are randomly distributed, we do not only generate supply-demand relations between firms and customers, but also links between two customers or between two firms. These links, shown in red in Figure 1a, are seen as negative because of an assumed competition. Firms compete for customers to sell their products, customers compete to meet their individual demand.

Links between customers and firms (black) are seen as positive because of assumed supply-demand relations. We define the degrees as $k_i = k_i^{\mathrm{p}} + k_i^{\mathrm{n}}$ and $k_K = k_K^{\mathrm{p}} + k_K^{\mathrm{n}}$, to distinguish the positive supply-demand relations, $k_i^{\mathrm{p}}, k_K^{\mathrm{p}}$ from the negative links $k_i^{\mathrm{n}}, k_K^{\mathrm{n}}$. In this paper we will not model competition, but consider that some supply-demand relations may not be utilized if the firms cannot supply the environmental-friendly products demanded by the customer.

The network of supply-demand relations determines which firms can supply a specific customer, and which customers have a demand for the products supplied by a specific firm, on the other hand. Therefore the individual demand and supply is now fragmented with respect to the available counterparties:

$$d_i = \sum\nolimits_{J \in \|k_i^{\mathrm{p}}\|} d_{iJ} \;; \quad d_{iJ} = \frac{d_i}{k_i^{\mathrm{p}}} \qquad s_K = \sum\nolimits_{j \in \|k_K^{\mathrm{p}}\|} s_{Kj} \;; \quad s_{Kj} = \frac{s_K}{k_K^{\mathrm{p}}} \tag{1}$$

$\|k_i^{\mathrm{p}}\|$ denotes the set of firms J which have a supply-demand relation to customer i. Likewise, $\|k_K^{\mathrm{p}}\|$ denotes the set of customers j which have a supply-demand relation to firm K. We have assumed that each firm splits its production equally to supply the available customers and each customer splits its demand equally among the available suppliers. Changes to this rule are discussed in Section 3.1.

The fact that customers are only supplied by specific firms can result in a situation where their demand d_i cannot be satisfied by these firms. I.e., there can be a *supply deficit* for some customers. Also, some firms with a larger supply may not have enough customers, therefore they face a *demand deficit*. To be more specific, for customers we define, in addition to the demand d_i, a value $\hat{d}_i$ that denotes the total number of products that customer i in fact received from its suppliers. Likewise, for firms we define, in addition to the supply s_K, a value $\hat{s}_K$ that denotes the total number of products that firm K has in fact sold to its customers.

$$\hat{d}_i = \sum\nolimits_{J\in\|k_i^{\mathrm{p}}\|} \min\left(s_{Ji},\ d_{iJ}\right) \quad ; \quad \hat{s}_K = \sum\nolimits_{j\in\|k_K^{\mathrm{p}}\|} \min\left(d_{jK},\ s_{Kj}\right) \tag{2}$$

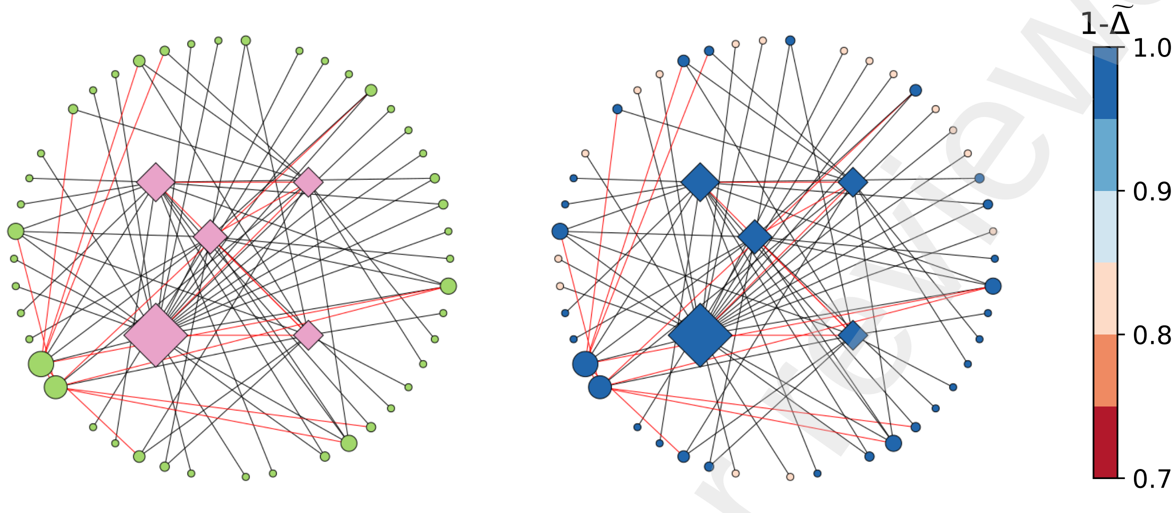
The $\min(a, b)$ function ensures that the supply from neighboring firms cannot exceed the demand of customer i and the demand from neighboring customers cannot exceed the supply of firm K.

$\Delta d_i = d_i - \hat{d}_i > 0$ then indicates a *supply deficit* for customer i and $\Delta s_K = s_K - \hat{s}_K > 0$ indicates a *demand deficit* for firm K, which means firm K is *over-producing*. Since customers and firms have heterogeneous values of demand and supply, we also define the relative supply deficit $\widetilde{\Delta} d_i = \Delta d_i/d_i$ and relative demand deficit $\widetilde{\Delta} s_K = \Delta s_K/s_K$. These supply and demand deficits solely result from the *local* mismatch between firms and customers. In a global market where all customers interact with all firms we have assumed that global supply always equals global demand, on average.

Figure 1b shows the supply-demand network with the resulting deficits for both firms and customers. With the given local network configuration, 16 of the 45 customers can only cover less than 85% of demand (in red) from their current suppliers. The mitigation of possible *local* supply-demand deficits is the main target for our following investigations.

2.3 Modeling environmental consciousness

The method so far describes the *baseline* needed to measure the impact of environmental consciousness, η, on the supply-demand relations. In general η indicates the level of concern for environmental issues [1]. For instance, firms with a high environmental consciousness are assumed to offer products which are more environmental-friendly, while customers with a high environmental consciousness have a strong preference to buy only environmental-friendly products [19]. Such preferences can induce a adaptation process in firms. Indeed, firms are willing to produce environmental-friendly products when facing sufficient pressure from customers [12, 36].



(a) **(b)**

Figure 1: (a) Network of supply-demand relations between firms (diamonds) and customers (circles). The size of the symbols is proportional to the number of links. (b) The same network, now encoding the relative supply deficit $\widetilde{\Delta}d_i$ of customers and the relative demand deficit $\widetilde{\Delta}s_K$ of firms by means of a color code of the nodes. Blue colors indicate $1-\widetilde{\Delta}d_i$ and $1-\widetilde{\Delta}s_K$ are satisfactory as they are above 85%.

In our model η is considered an internal variable of both customers and firms which is heterogeneous, i.e. it varies across agents, and can be changed in time according to a dynamics described in Section 3.1. Initially, we sample the values η_i, η_K from ad uniform distribution $U(1,2)$, but we note that over time η can reach larger or smaller non-negative values.

To operationalize the environmental consciousness of firms, we relate it to the carbon emission policy of the firm in an abstract manner. We simply assume that firms with a high η_K generate less carbon emissions and vice versa. Hence, if s_K is the supply of products of firm K and η_K its current level of environmental consciousness, then $E_K = s_K/\eta_K$ proxies its current level of carbon emission. If firm K supplies k_K^{p} customers, then the carbon emission per customer is: $e_K = E_K/k_K^{\mathrm{p}} = s_K/[\eta_K k_K^{\mathrm{p}}]$.

Customers, on the other hand, are sensitive to this information, which is assumed to be public. Dependent on their own environmental consciousness $\eta_i(t)$, they prefer to be supplied by firms with a matching $\eta_K(t)$. To operationalize this preference, we define a *utility* u_{iK} of customer i supplied by firm K. u_{iK} is a Boolean variable, i.e. $u_{iK} = 1$ if customer i accepts the supply of firm K and $u_{iK} = 0$, otherwise. To determine the acceptance, customer i compares the carbon emissions per customer of firm K, e_K with a *threshold* ε_i. This threshold reflects not only the customer's own environmental consciousness, η_i, but also its demand, d_i, and its degree, k_i^{p}, i.e. its available options to be supplied. We assume initially an equal demand from all neighboring firms, i.e. the customer has a demand of d_i/k_i^{p} from each firm. This is weighted with its own sensitivity to carbon emissions, hence its threshold is $\varepsilon_i = d_i/[\eta_i k_i^{\mathrm{p}}]$.

Finally $u_{iK} = \Theta[\varepsilon_i - e_K]$, where the Heaviside function is $\Theta[x] = 1$ if $x \geq 0$ and $\Theta[x] = 0$ otherwise.

Considering the customer's utility, we can now have a situation in which firm K may want to supply customer i with a fraction s_K/k_K^p of products, but customer i refuses it because it does not tolerate the carbon emissions associated with the production of firm K. So, we still have a relation between i and K, indicated by a link in the network, but this link is not utilized. Precisely, u_{iK} informs whether the supply-demand relationship is effective or not.

This situation is illustrated in Figure 2. Comparing the supply-demand deficit with the baseline case shown in Figure 1b, we find that now most firms and most customers face a deficit. Firms have a surplus of products they cannot sell because customers require more environmental-friendly products, and customers cannot satisfy their demand because they do not accept the supplied product quality. The mismatch is shown in Figure 2 by the large number of red links which, in addition to competition, now also indicate $u_{iK} = 0$. This scenario sets the stage for our main investigation, namely how to mitigate the supply-demand deficit observed.

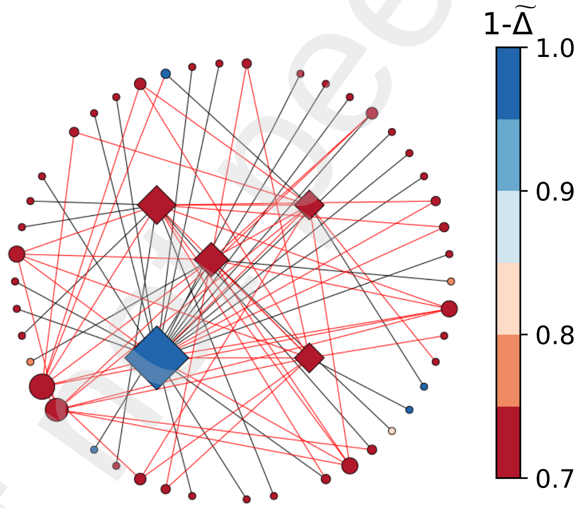


Figure 2: Network of supply-demand relations between firms and customers already shown in Figure 1a. The color code indicates the relative supply deficit $\widetilde{\Delta}d_i$ of customers and the relative demand deficit $\widetilde{\Delta}s_K$ of firms, now taking their respective environmental consciousness η_i, η_K into account. Red links between customers and firms indicate $u_{iK} = 0$, i.e. the supply-demand relation is not utilized.

3 Calculations

3.1 Simulating adaptation scenarios for customers and firms

The calculations of our model are in fact *simulations* of the agent-based model specified above. The difference is in the random elements involved in generating the dynamics. To solve the full model we do not have a set of coupled differential equations, but a set of rules that are formalized and followed with a given probability. Specifically, in the full model described in Section 3.2, customers can choose between adapting their environmental consciousness η_i or establishing new links to suppliers. To understand the impact of such choices on mitigating supply-demand deficits, we first need to calculate what is the outcome when considering the adaptation dynamics, only. This is done in the following.

Given that customers do not utilize certain relations to their supplying firms because of environmental concerns, i.e. $u_{iK} = 0$, they have to increase their demand from those suppliers they still accept, i.e. $u_{iK} = 1$. To reflect this, we have to replace the assumption of equal demand from all supplying firms, d_i/k_i^{p}, Eqn. (1), by an assumption that (i) considers the utility of relations and (ii) favors firms with higher environmental consciousness, i.e. with lower carbon emissions.

From Eqn. (2) we recall that the satisfied demand of customer i is given by $\hat{d}_i$, which is the sum over all fractional supplies s_{Ji} from neighboring firms. Each of these s_{Ji} is associated with a fractional carbon emissions, s_{Ji}/η_J. Hence the carbon emissions resulting from the total demand of customer i is

$$E_i = \sum\nolimits_{J\in\|k_i^{\mathrm{p}}\|} f_{Ji}\ ; \quad f_{Ji} = \frac{s_{Ji}}{\eta_J} \tag{3}$$

Customer i tries to decrease its fractional demand d_{iK} from those firms that have a lower η_K and to increase its demand from firms with a higher η_K which is reflected by the following choice function:

$$d_{iK} = u_{iK}\ d_i \frac{e^{(-\eta_i\cdot f_{Ki})}}{\sum\nolimits_{J\in\|k_i^{\mathrm{p}}\|} e^{(-\eta_i\cdot f_{Ji})}} \tag{4}$$

This function ensures that only supply relations with positive utility are utilized, $u_{iK} = 1$, and that suppliers with a lower carbon emission f_{Ki} are preferred. Additionally it also considers the environmental consciousness η_i of the customer. If η_i becomes large, even small differences in the carbon emissions of the suppliers can make a large impact on the choice of the customer. If $\eta_i \to 0$, the opposite results: the carbon emissions of firms obtain less weight, i.e. the customer cares less about it. In the limit case, where $\eta \to 0$ for all customers and firms, we have $\sum_J u_{iJ} = k_i^{\mathrm{p}}$, which means a fractional demand $d_{iK} = d_i/k_i^{\mathrm{p}}$ as assumed for the baseline case, Eqn. (1).

For the supply of firms, we still use the assumption of an equal distribution across customers, Eqn. (1).

However, we take into account that some relations are not utilized, i.e. $s_{Kj} = u_{jK} s_K / k_K^p$. As a result, firm K may not be able to sell its production to the neighboring customers because the supply is not accepted, i.e. it faces a *demand deficit*. We note that with the choice function, Eqn. (4), a *supply deficit* for customers can still result because the requested supply may be too much for firm K.

Taking the environmental consciousness of agents into account, there are three different scenarios of resolving deficits: (i) *customers* can reduce their η_i to accept supply from firms with a higher carbon emission, (ii) *firms* can increase their η_K to become acceptable for a larger range of customers, or (iii) customers and firms establish *new relations* to mitigate deficits. The latter implies that the *network topology* changes in response to customers' and firms' preferences and is discussed in Section 3.2.

In the following, we evaluate the first two scenarios separately. In the first simulation, we assume that customers decrease their environmental consciousness η_i in case of a supply deficit. In the second simulation, we consider that firms increase their environmental consciousness η_K in case of a demand deficit. The dynamics reads:

$$\begin{aligned} \eta_{i,t+1} &= \eta_{i,t} \left(1 - r_c\right) \\ \eta_{K,t+1} &= \eta_{K,t} \left(1 + r_f\right) \end{aligned} \tag{5}$$

Our simulations start from the configuration shown in Figure 2 and run for 5 time steps, which is sufficient to converge to a stationary state in which deficits not change anymore. The values r_c, r_f denote the increase, or decrease respectively, of the environmental consciousness in case that a supply or a demand deficit still exists.

The results of the two separate agent-based simulations are shown in Figure 3, which should be compared to Figure 2 without adjustment of η. We observe that the supply deficits of customers and demand deficits of firms have reduced in both cases. This is expected because firms increasing their η_K may turn negative relations with customers into positive ones and, additionally, customers with positive relations will increase their demand from the environmental-friendly firms. Likewise, customers decreasing their η_i will have more positive relations with supplying firms, as indicated by the disappearance of red links.

It should be noted that, dependent on the initial topology of the supply-demand network, also counter intuitive situations appear. In the first scenario, the supply deficit of customers can also *increase* instead of decreasing after lowering their η_i. We recall that customers with a low η_i will demand comparably more products from firms with a high fractional emission f_{Ji}, Eqn. (4). Because firms supply the same fraction s_K / k_K^{p} to their customers, this can then lead to a supply deficit for those customers that only have a few supplying firms.

In Figure 4 we show how the environmental consciousness values of customers and firms changed for the two scenarios. Initially all values were sampled from the interval $U(1, 2)$. From the final distri-

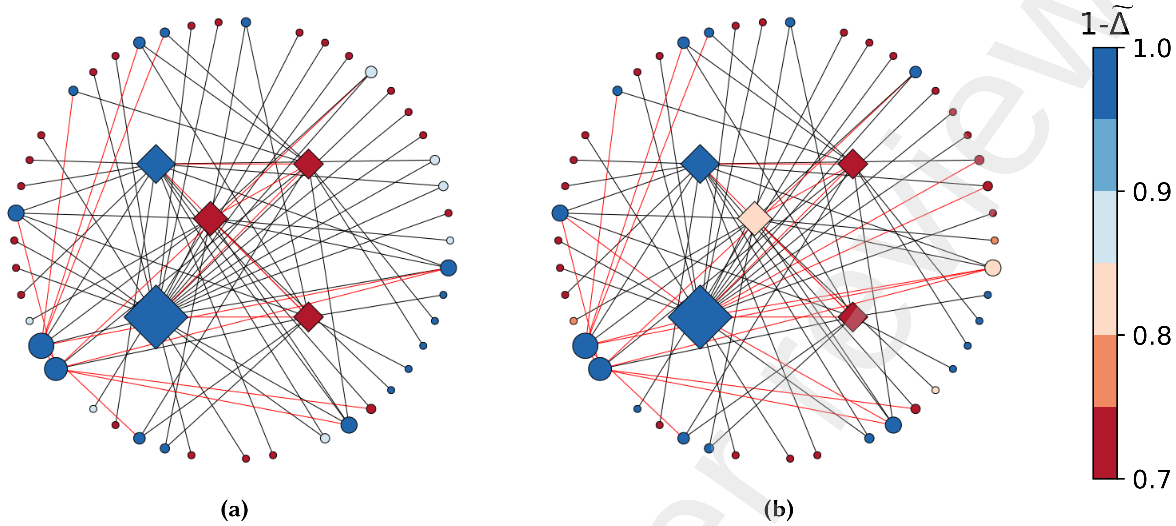


Figure 3: Network of supply-demand relations between firms and customers after adjusting their environmental consciousness in response to a deficit: (a) After decreased η_i of customers, with $r_c = 0.65$, while keeping the η_K of firms constant. (b) After increased η_K of firms, with $r_f = 0.5$, while keeping the η_i of customers constant.

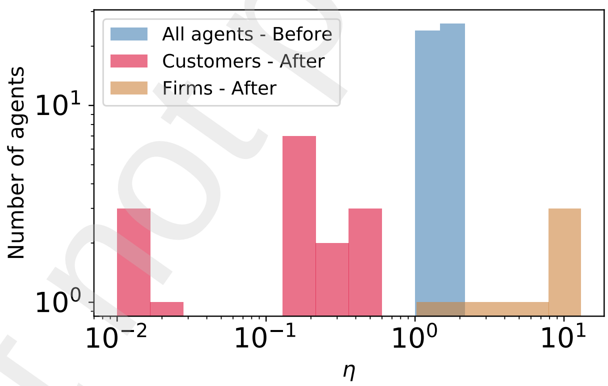


Figure 4: Changes in the distribution of the environmental consciousness of customers, η_i and firms, η_K from Figure 2 to Figure 3. (blue) initial values, (orange) final values for firms, (red) final values for customers.

butions we see that most customers considerably reduced their η_i to mitigate their supply deficit, while firms considerably increased their η_K to mitigate their demand deficit. One could argue that the final values strongly depend on the choice of r_c, r_f, but this is not the case as we have verified independently. Above a critical value of about 0.3, we do not find a further reduction of demand deficits. Most customers and firms do not succeed, as clearly indicated by the red colored nodes in Figure 3. This is partly to be expected because basic limits to reducing the supply and demand deficits result from the network topology. It explains why the smaller firms are still over-producing although they have radically increased η_K. The largest firm, however, supplies a lot of customers already and therefore only needed to slightly increase its η_K.

In summary, we see that, despite considerable changes in η_i, η_K, the overall reduction of the supply and demand deficits is not very strong. Therefore, to improve the results shown in Figure 3, we need to combine the adjustment dynamics with the possibility of changing supply-demand relationships between customers and firms.

3.2 Simulating new supply-demand relationships

In addition to adjusting the environmental consciousness η_i, η_K, Eqn. (5), customers and firms can mitigate the supply-demand deficit by choosing new counterparties. This implies changing the topology of the network according to some rules specified below. We do not start from an empty network but use the network with a large supply-demand deficit shown in Figure 2 as our initial configuration.

Customers with a supply deficit now have two options to resolve their situation: With a probability p_c they can decrease their environmental consciousness η_i as described above in Eqn. (5). With a probability $(1 - p_c)$ they can instead establish a new relation to a firm they are not already linked to. For the formation of new links we consider different rules:

[a] *Unilateral* link formation: the customer establishes a link to another firm *randomly*, and the firm has to accept this.

[b] *Bilateral* link formation: the firm will accept a new link from a customer only if it has a demand deficit.

[c] *Smart* link formation: the customer establishes a link to another randomly chosen firm only if this warrants a positive utility, $u_{iK} = 1$. The firm has to accept the link.

We wish to point out some implications from the different rules, first. Rule [a] will not prevent customers from establishing new links that are not utilized, i.e. $u_{iK} = 0$. This may be seen a drawback at first sight because a good opportunity to mitigate the supply deficit seems to be wasted, which denotes the main difference to rule [c]. However, because no new negative relations are formed under rule [c], there is also no chance that such relations can become positive in the next time step. This chance is not small, firstly because both customers and firms adjust their environmental consciousness η with a certain probability. Secondly, more customers reduce the carbon emissions per customer, e_K, of firm K, which increases the chance for other customers to turn a negative into a positive relation. Rule [c] instead limits the choice of possible firms for establishing new links drastically, which could lead to a future disadvantage.

Rule [b] also seems to be "smart" because both the perspectives of the customers and the firms are taken into account. Why should a link be formed to a firm that already supplies all its products and has no over-production? Again, this argument neglects changes in the near future which result from the adjustments of the η_i, η_K and the formation of links from other customers. As we will see, having more links to diverse suppliers, even if these are not always utilized, is a good way to mitigate supply deficits, and better than restricting the relations to positive ones.

For firms we only assume that, with a certain probability p_f, they reduce their environmental consciousness η_K as described in Eqn. (5), while with probability $(1-p_f)$ nothing happens. That means, only customers initiate the formation of new supply-demand relationships and firms, with the exception of rule [b], have to accept this.

With these assumptions, we have four free parameters, r_c and p_c for customers and r_f and p_f for firms that determine the dynamics. The existing non-linear feedback between the different options, i.e. changing η_i vs. changing the network, makes it hard to predict which combination of parameters will lead to the optimal mitigation of the initial supply-demand deficits, on the systemic level.

4 Results

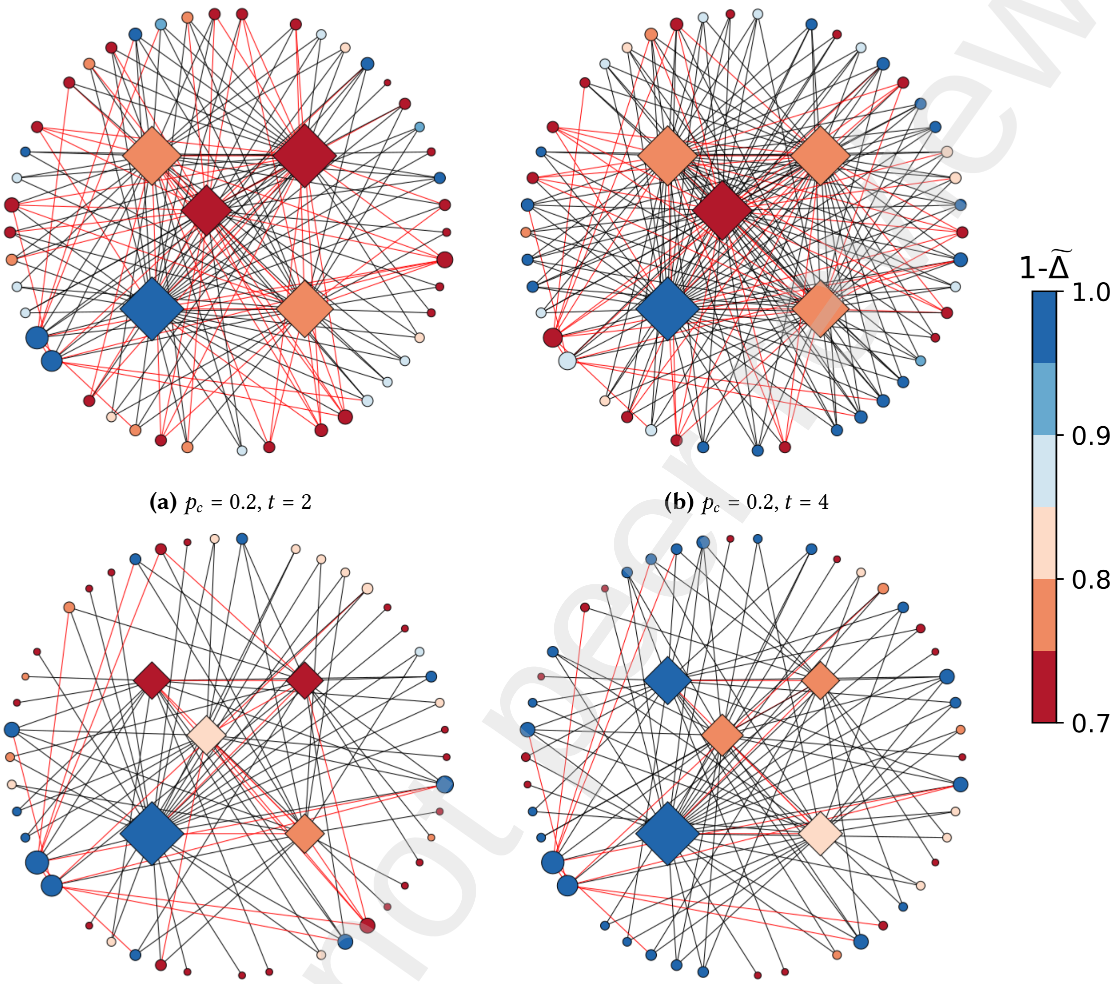
4.1 Mitigating supply-demand deficits

Because we have not restricted the number of newly formed links, the supply-demand network over time will become a fully connected network. This network, by design, will not have any supply or demand deficits, because the global supply equals the global demand. Hence, it is more interesting to restrict the simulations to the 5 time steps used before, to make the mitigation results comparable.

To give some intuition about the dynamics for different link probabilities p_c, in Figure 6 we show the temporal evolution of the supply-demand network for two intermediate time steps, using rule [a] and starting from Figure 2 at $t = 0$. The most obvious difference of the two simulations is in the network density, which by design increases with the probability to form new links, $(1 - p_c)$.

In which of the two cases the supply-demand deficit is better mitigated, is not so obvious. Therefore in Figure 6 we provide the results of a parameter sweep to find optimal parameters for minimizing the deficit. This requires us to first define an aggregated quantity that reflects the systemic deficit. We define the *total* relative demand covered for all customers, C, as

$$C = \frac{\sum_{i=1}^{N_c} \hat{d}_i}{\sum_{i=1}^{N_c} d_i} \tag{6}$$



(a) $p_c = 0.2, t = 2$ **(b)** $p_c = 0.2, t = 4$

(c) $p_c = 0.85, t = 2$ **(d)** $p_c = 0.85, t = 4$

Figure 5: Change of the supply-demand network with unilateral link formation (rule [a]) and two different link probabilities.

Here $\sum_{i=1}^{N_c} \hat{d}_i$ is total the demand of all customers actually covered by supply. Ideally, C should reach values close to 1, indicating that supply deficits have vanished.

We find that the optimal parameters for maximizing C are $(p_f, r_f, p_c, p_c) = (0.9, 0.9, 0, 0)$. That means firms should always increase their environmental consciousness, while customers should only create new links. We explore this finding in Figure 6. Since visualizing a four-dimensional parameter space is very hard, we instead report the C values when varying the customers' (firms') parameters while fixing the firms' (customers') parameters at their optimal values. By this, we explore what is the role of customers' (firms') parameters when the the others are already doing their best to increase the C. From Figure 6(a), we find that, using fixed optimal parameters for firms, an adjustment of the environmental consciousness of customers η_i does not reduce the supply deficit a lot. That means it is much better when customers only create new links to increase the total demand covered. In Figure 6(b), we use optimal parameters for customers and find that both r_f and p_f should stay high to keep C high. That means firms should always increase their environmental consciousness as much as possible. When not doing this, the demand covered can become less than 70%. To conclude, the total relative demand covered, C, is maximized if customers continuously establish new relations, while firms continuously do their best to keep these relations positive.

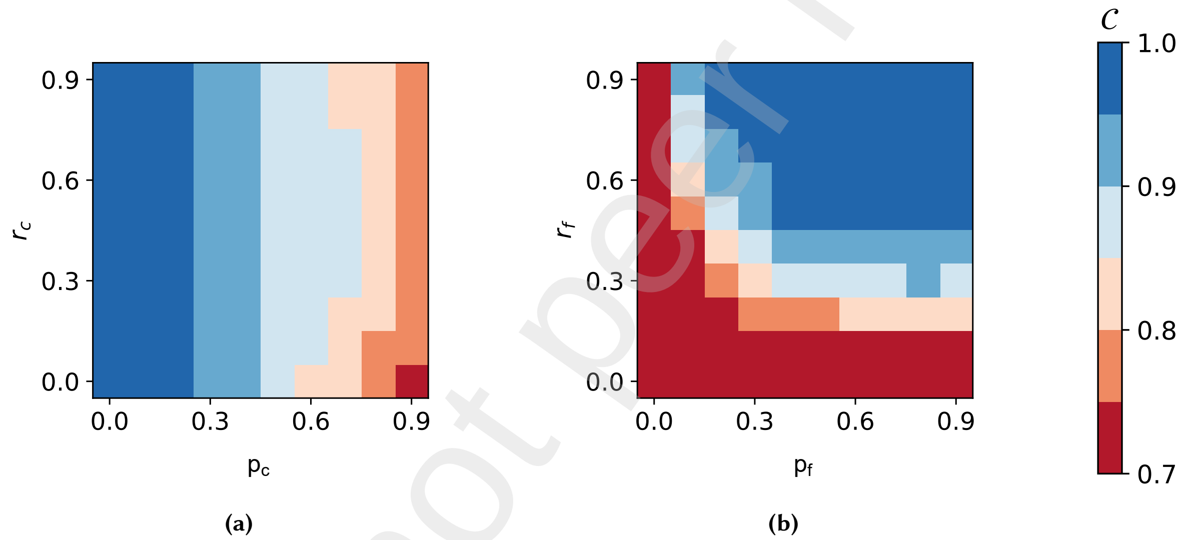
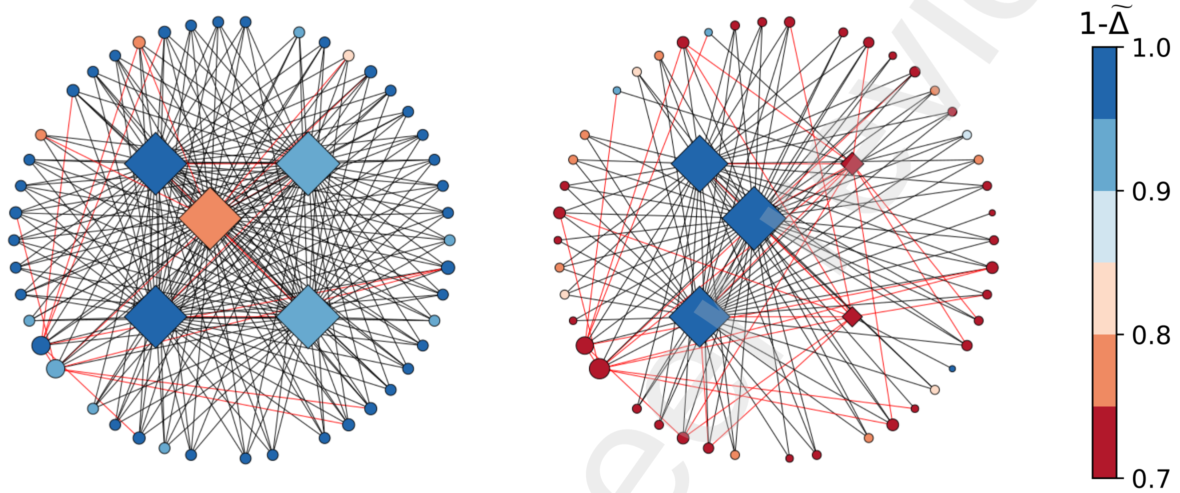


Figure 6: Color coded total relative demand covered, C, Eqn. (6) (a) for different customer parameters (r_c, p_c), using optimal firm parameters ($r_f = 0.9$, $p_f = 0.9$), (b) for different firm parameters (r_f, p_f), using optimal customer parameters ($r_c = 0$, $p_c = 0$).

The questions remains whether the other two rules for link formation, [b] and [c], would further improve the situation. We have repeated the full parameter sweep also for these two cases, to conclude that the graphs look very similar to the ones presented in Figure 6, with a noticeable deterioration for intermediate parameter values. But the optimal parameters to maximize the relative demand covered, C, remain the same as for the unilateral link creation rule [a].

The explanation for this has been already mentioned when the three rules were introduced. If customers only create positive relations, they miss the opportunity that negative relations can later turn into positive ones and then contribute to their supply. The chances that negative relations change to positive ones are quite high. Therefore, creating new relations unconditionally appears to be the best strategy to reduce supply deficits. Network density matters in the end. To visualize the resulting difference, in Figure 7 we plot the final networks created by rules [a] and [c], using the same parameters for customers and firms. Still, because for rule [c] only positive relations are established, the network is less dense, despite the same high probability for link formation.



(a) Rule [a]

(b) Rule [c]

Figure 7: Suppy-demand network at $t = 5$ for $f_a = 0.4$ $f_r = 0.4$ and $p_c = 0$, $r_c = 0$. This is the sub-optimal scenario in which C under rule [a] and rule [c] differs the most.

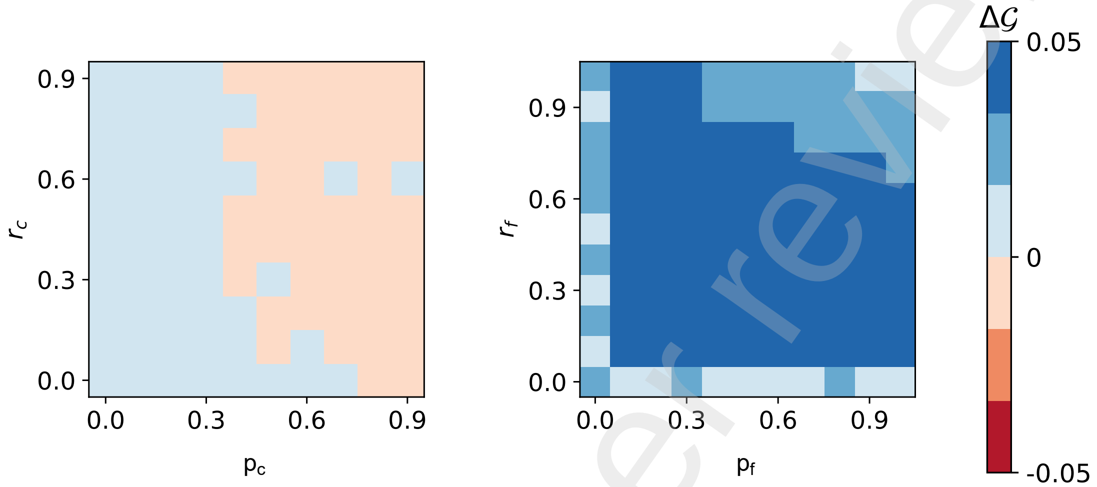
4.2 Mitigating inequalities in supply deficits

To further evaluate the supply-demand mismatch from the customers' perspectives, we eventually study the *distribution of demand deficits* across customers. For this we apply as the second aggregated measure, the *Gini coefficient* $\mathcal{G}$ [37]:

$$\mathcal{G} = \frac{1}{2N_c^2 \langle \hat{d} \rangle} \sum_{i=1}^{N_c} \sum_{j=1}^{N_c} \left| \hat{d}_i - \hat{d}_j \right| \tag{7}$$

$\mathcal{G}$ is used in economics to evaluate inequalities of income or wealth in society [38]. Here we quantify the heterogeneity in demand deficits among customers. $\mathcal{G}$ varies from 0 to 1. Higher values indicate a higher inequality of the respective distribution.

We emphasize that, even if all customers have solved their supply deficit, the inequality measure $\mathcal{G}$ is still less than 1, simply because the initial demand d_i is already heterogeneous across customers. Therefore, in the following we will focus on *changes* of the Gini coefficient, $\Delta\mathcal{G}$, dependent on rules [a] and [c]. Negative values of $\Delta\mathcal{G}$ indicate that the inequality of deficits is larger for rule [a] than for rule [c], whereas positive values indicate that rule [a] is more effective in reducing supply deficits.



(a) Optimal firms parameters **(b)** Optimal customers parameters

Figure 8: Color coded differences $\Delta\mathcal{G} = \mathcal{G}_c - \mathcal{G}_a$ between rules [c] and [a]: (a) for different customer parameters (r_c, p_c), using optimal firm parameters $(r_f = 1, p_f = 1)$, (b) for different firm parameters (r_f, p_f), using optimal customer parameters $(r_c = 0, p_c = 0)$.

Figure 8 summarizes the differences $\Delta\mathcal{G}$ comparing rule [a] and rule [c]. Figure 8a assumes optimal parameters for firms, $p_f = 1, r_f = 1$, to vary the parameters for customers. We can clearly distinguish two regions. For low values of p_c, i.e., for high link probabilities, $\Delta\mathcal{G}$ is slightly positive, which means that rule [a] results in a lower deficit inequality than rule [c]. For high values of p_c, i.e. for low probabilities of forming new links, rule [a] pales against rule [c] because of a higher deficit inequality.

Figure 8b assumes optimal parameters for customers, $p_c = 0, r_c = 0$, to vary the parameters of firms. Here we find that for all ranges of parameters rule [a] always results in a lower inequality than rule [c]. As Figure 7 illustrates, customers suffer more from supply deficits under rule [c]. This results in a greater inequality compared to rule [a].

The more interesting insight is indeed provided by Figure 8a where we see an advantage for rule [c] in the range of larger values of p_c. When only few new links are established, it is better for customers to create only positive relations. These, however, do not increase inequality much. With rule [a], customers can create a link with a firm with few customers and receive a large portion of the supply. Hence, this will increase inequality more than under rule [c].

We note again that a denser supply-demand network favors a mitigation of supply deficits. Thus, while demands remain heterogeneous, rule [a] ensures that most customers can completely reduce their supply deficit. The large number of positive relations shown in Figure 7a helps to reach this state.

Because in the final state at $t = 5$ firms have reached a high environmental consciousness, customers utilize almost all of their relations. This means they have a comparable amount of positive links. If they still miss a link to a firm, they do not miss much in terms of supply because, with a large number of customers, each positive relationship only provides a small amount of products. Therefore the final network topology shown in Figure 7a is most efficient in reducing the Gini coefficient.

5 Discussion

Our agent-based model of establishing supply-demand relations between customers and firms provides novel insights in different respects. Firstly, we *operationalize* an *internal* variable, *environmental consciousness* η, which is heterogeneous and can change over time. Quantifying environmental consciousness is difficult [18] because it depends on psychological and sociological concepts such as value, awareness, norms, or engagement. We get around this problem by modeling the *external* consequences, i.e. the resulting actions, of a high or low environmental consciousness, which becomes *public information* this way. Our model only uses the reasonable argument that customers with a high η_i prefer to not buy products from firms which are known to be environmental polluters. Firms, on the other hand, can respond to this drop-down in demand, by increasing their environmental consciousness, e.g. by reducing the carbon emission per product. However, if customers face a supply deficit, they may decide to lower their standards, expressed in their η_i, rather than staying unsupplied. This feedback externalizes an internal reasoning without reference to psychological or sociological details.

Secondly, our model allows to study the impact of different scenarios to *mitigate* supply deficits of customers or demand deficits of firms. The origin of these deficits is *not* the insufficient production of goods, we always ensure that global supply equals global demand. These deficits result from a *local* mismatch between the available production of firms and the demand of those customers that have these firms as suppliers. Hence, we study the *network* of existing *supply-demand relations* rather than a globalized market for distribution. This approach enables us to distinguish the dynamics *on* the network, i.e. changes in the supply or demand on existing links, from the dynamics *of* the network, i.e. changes of the link structure itself. Studying combinations of these two dynamics, expressed in only four parameters, we can identify which scenarios are most efficient in mitigating these supply and demand deficits.

Our interesting finding suggests that customers should concentrate on establishing new links to firms, no matter whether these links can be actually utilized. Firms, on the other hand, should concentrate on increasing their environmental consciousness to remain attractive for customers. This implies that customers should *not* compromise on their environmental consciousness as long as they have the chance to form new relations. We have also shown that more rationality in establishing new links does not lead to a better mitigation of deficits. From the three rules we investigated for the formation of new links, the unconditional link formation performs better than rules that condition on the acceptance of firms or on the positive evaluation of environmental consciousness.

We note that mitigation scenarios that *only* target the dynamics *on* the network by increasing the η_K of firms or decreasing the η_i of customers, are not sufficient to resolve the deficits. The best results are obtained by *combining* changes for the dynamics *on* and *of* the network. This will not only reduce demand and supply deficits, it will also reduce the carbon emission of production if firms decide to increase their η_K.

6 Conclusions and future work

The insights obtained from our agent-based model can support policy advice regarding (i) the role of environmental consciousness and (ii) the mitigation of supply-demand deficits. The latter should be of high concern for policy makers interested to avoid shortages on supply, but also inefficient production.

Our model has shown that the environmental consciousness of customers can become a strong motivational factor for firms to reduce their emissions. Hence, firms should be enabled to better know the environmental consciousness of their customers and adapt to it. This could be achieved by surveys and data bases to disclose customers' environmental consciousness in different economic sectors [39]. Further, firms should become more aware of how customers themselves assess the environmental consciousness of firms [40]. To become successful, this policy requires a high, or at least a constantly increasing, environmental consciousness of customers. This can be achieved by means of environmental education [17] or sustainable advertising [16].

To reduce supply-demand deficits, our model demonstrates the crucial role of *diversification* in suppliers. This insight is in line with the policy conclusions drawn from the recent economic crises. But our model additionally emphasizes the importance of unconditional supply links. It is almost trivial that new supply links should be established *if* they reduce a current supply deficit. As we have seen, this drastically limits the possibilities of diversification. Our model has shown instead that even supply links that are currently not utilized can become important in the near future. Therefore, opportunities for diversification should be evaluated not only from the present, but also with future developments in mind. This, however, requires to better estimate the future impact of supply decisions [41], both for customers and for institutions. If policies encourage firms to disclose their *future plans for carbon emissions reduction* [42], customers could take this information into account when making long-term supply decisions.

The model further highlights the *double impact* of environmental consciousness in reducing emissions, as summarized in the choice function of Eqn. (4). If customers can raise their environmental consciousness, they will choose more products from environmental-friendly firms. Firms have thus a stronger incentive to further improve their environmental consciousness, to attract more demand. This increases the competition with other firms that face a pressure to catch up. That means the feedback mechanism underlying our model can be leveraged as a *virtuous cycle* of continuous improvement, if policies support this direction. However, if policies fail to do so, the same feedback mechanism can lead to a *vicious cycle* of accelerating degradation. Thus, we need to raise the awareness for such scenarios in policy makers.

Our model can be extended in different directions, some of which will be addressed in subsequent publications. In a first step, we can add top-down regulations to the model to study, e.g., the impact of environmental standards [43] on customer-firm relationships. This perspective will complement our bottom-up approach to mitigate supply-demand deficits.

Secondly, we will focus more on the role of negative relations that by now reflect only the mismatch of environmental consciousness between customers and firms. In principle, negative relations can also describe competition between customers to be supplied by specific firms, or competition between firms for customers. With this extension, the supply-demand network can be turned into a *signed network* [44]. This allows to study its structural balance as a measure of network robustness [45].

Eventually, we can also extend the notion of positive relations to firm-firm or customer-customer interactions. Customers, for instance, would then not only compete, but also collaborate to form buyer coalitions [46] to strengthen their position against suppliers. With these extensions, we turn the bipartite and signed network into a multi-layer network [47] where intra-layer links in one layer describe the interactions between customers, intra-layer links in another layer the interactions between firms and inter-layer links between layers the interactions between customers and firms. Such multi-layer networks can be used to simulate the propagation of supply shocks [48] and the resulting supply deficits [49]. This way, a successive increase of complexity can turn our agent-based approach into a modeling framework to formally study the resilience of supply-demand networks.

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