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The introduction of a new product or service into society can have detrimental effects on the environment due to changes in usage and practices. Human-Computer Interaction (HCI) designers need practical methods to address it. In this paper, we explore whether systemic modeling could help designers understand and mitigate these rebound effects. Drawing on systemic design and system dynamics, we prototyped a collaborative modeling methodology that ten professional designers applied to a case study in two workshops. We share insights on their adoption of the methodology and their feedback on its usefulness, usability, and feasibility. Our results indicate that designers find the systemic modeling approach relevant and useful for addressing rebound effects. Influence diagrams can help structure design ideas and identify unaddressed points, while dynamic modeling can help compare design strategies. Based on these findings, we propose a framework for integrating this approach into a design process.

CCS CONCEPTS • Social and professional topics → Sustainability; • Human-centered computing → HCI design and evaluation methods; • Social and professional topics → Socio-technical systems.

Additional Keywords and Phrases: Sustainable HCI, Rebound effect, Systemic approach, Design methods, Collaborative modeling

ACM Reference Format:

First Author's Name, Initials, and Last Name, Second Author's Name, Initials, and Last Name, and Third Author's Name, Initials, and Last Name. 2018. The Title of the Paper: ACM Conference Proceedings Manuscript Submission Template: This is the subtitle of the paper, this document both explains and embodies the submission format for authors using Word. In Woodstock '18: ACM Symposium on Neural Gaze Detection, June 03–05, 2018, Woodstock, NY. ACM, New York, NY, USA, 10 pages. NOTE: This block will be automatically generated when manuscripts are processed after acceptance.

1 Introduction

Sustainable Human-Computer Interaction (SHCI) brings together HCI research efforts towards a more sustainable future. At first, these initiatives focused mainly on the direct material impact of a system (especially energy), by optimizing the system itself and encouraging users to reduce their consumption through persuasive design [36]. As early as 2014, members of the SHCI community recognized that these endeavors were insufficient and called for a systemic approach to address the complexity of sustainability [18] [32] [53]. Since then, numerous initiatives have emerged, such as engaging with communities, co-design activities, non-interventional studies, speculative design, and more-than-human design, and the community has "*moved towards more diverse, qualitative and speculative SHCI research*" [10].

Even though these initiatives are important and should not be discarded, they remain at a theoretical, provocative, or exploratory level, with local or unmeasurable impact. According to Bremer et al.'s analysis [10], they fall short in addressing the urgency of the situation. In particular, *rebound effects* are complex phenomena that are scarcely considered or only mentioned in Sustainable HCI [9], yet they are crucial when designing for sustainability [9] [14] [60]. Indeed, the introduction of a new product (or service) into society can have *indirect effects*, whether positive or negative, on the environment, due to the changes it causes in usage and/or practices at the sociotechnical level [14]. When negative impacts arise from these mechanisms, they are commonly referred to as *rebound effects* [23]. Given its pivotal position between humans and technology, its ability to study sociotechnical phenomena, and its holistic and interdisciplinary approach, the HCI community could play a pioneering role in considering *indirect* and *rebound effects* [9] [41].

The question remains of how to equip HCI designers to confront those phenomena, some of which are acknowledged to be highly uncertain and complex [5]. Systems thinking, system dynamics, and systemic design are seen as particularly relevant for explaining systemic effects [4] [7] [9] [37] [60]. Modeling and simulating system dynamics could offer a promising opportunity to understand their magnitudes, anticipate their effects over time, and explore mitigation design strategies [6] [25]. However, the literature lacks concrete examples of the use of systemic methods and modeling in the design process to address rebound effects. Furthermore, designers may not be familiar with dynamic modeling [25].

The contribution of this paper is an investigation of the potential of collaborative systemic modeling and its possible integration into a design process by observing how designers adopt this methodology and gathering their perceptions and needs. To this end, we developed a methodological prototype by adapting appropriate systemic methods and tools, and conducted two workshops involving professional designers. In this study, designers found the systemic modeling approach promising for addressing rebound effects. Our workshops reveal that influence diagrams can help structure design ideas and identify unaddressed points, while dynamic modeling can help compare design strategies. Based on our findings, we propose a framework for integrating this approach into a design process.

We begin by providing an overview of the relevant literature. We then present our systemic modeling methodological prototype. Next, we introduce the case study and detail the structure of the workshops. Subsequently, we present the results and insights gathered from these workshops. Finally, we engage in a discussion about the contributions and the limitations of the workshops and suggest potential avenues for future research.

2 Related work and background

This section introduces key concepts and recent work that argues that HCI should address rebound effects. It details their methodological proposals to address rebound effects in HCI, and includes additional methodological inspirations from systems thinking and systemic design used in this paper to build the prototypical methodology.

2.1 Rebound effects

When we consider the environmental effects of a digital product or service, we generally distinguish between two types of effects: *direct effects*, which include the environmental footprint related to resource extraction, manufacturing, transportation, use, and end-of-life disposal, as well as associated equipment; and *indirect effects*, meaning the effects produced by the changes in usage and practices this product or service causes. Among these mechanisms, *rebound effects* typically refer to those that have negative impacts (such as increased energy, material consumption, emissions and/or pollutions), often by causing an increase in demand and production. When cost reductions, time savings, or other benefits associated with a product increase the usage of that same product, it is generally referred to as a *direct rebound effect* [24]. When these gains enable the use of other products or services that consume energy or resources, it is called an *indirect rebound effect* [24]. Finally, a *systemic or structural effect* [9] occurs when changes in individual behaviors become visible at the scale of the sociotechnical or socioeconomic system, altering practices, lifestyles, and patterns of consumption and production. In cases of *backfire*, the consequences exceed the initial savings. For instance, enhancing the efficiency of car engines enables drivers to save money, affording them the opportunity to drive more (*direct rebound*) or allocate their funds elsewhere, such as traveling by plane (*indirect rebound*). Some cities have been designed to accommodate cars, making them a necessity (*structural rebound*). As a result, there is an overall increase in fuel consumption (*backfire*).

2.2 The call to address rebounds effects in Sustainable HCI

Rebound effects have received limited attention in sustainable HCI until recently [9] [60]. However, HCI community seems well-positioned to address them due to its expertise in both qualitative and quantitative approaches, its holistic and interdisciplinary perspective, and its understanding of sociotechnical phenomena [9] [41]. HCI researchers could provide valuable insights to policymakers and other domains by contributing to the better understanding and measurement of rebound effects a posteriori. Furthermore, they could enhance the outcomes of their own projects by assessing the potential for rebound effects a priori and developing mitigation strategies [9]. In this article, we focus on the latter aspect: equipping HCI designers to understand rebound effects that may arise from their designs, comprehend their magnitudes, and adapt their design strategy accordingly. Bremer et al. [9] provide a taxonomy of HCI opportunities to identify, measure, explain, and mitigate various types of rebound effects, including direct, indirect, and structural. In particular, to understand and explain the mechanisms of rebound effects, they suggest drawing inspiration from the following methodologies: system dynamics [43], and systemic design methods [7].

2.3 Systems thinking and system dynamics

Systems thinking [3] [13] [40], originating in the 1960s, is a holistic and interdisciplinary approach that provides a framework for understanding complex problems or situations. This approach promotes considering problems within the context of larger systems instead of isolating individual parts and emphasizes understanding how components within a system interact. System dynamics [21] [56] is a methodology that is part of the broader framework of systems thinking. This mathematical modeling methodology is used to understand, analyze, and simulate the behavior of complex systems over time. System dynamics finds applications in diverse fields, including business management [56] and public policy design [39]. Among the various tools proposed by systems thinking and system dynamics, we are interested in those that best meet the need to collectively construct a dynamic model of the direct and indirect effects of a product or service. These concepts and tools are presented in the sections 2.3, 2.4, and 2.5. In particular, group model building is a methodology for collaboratively building models such as causal loop diagrams and stocks and flows.

Group model building [2] is a modeling approach that involves a diverse group of stakeholders working collaboratively to develop a conceptual model of a complex situation. The process typically starts with identifying the problem or issue of interest and defining the boundaries of the system being studied. The participants then engage in facilitated discussions and workshops to construct causal loop diagrams, system dynamics models, or other types of models (see Section 2.3). It allows participants to test various scenarios, simulate the behavior of the system under different conditions, and explore the potential consequences of different interventions or policy changes. Group model building has demonstrated its effectiveness across various contexts, including policy making and strategy development [49] [50]. However, to our knowledge, it has not been used to address rebound effects in the context of digital product or service design.

The main types of modeling used when describing sociotechnical phenomena are causal loop diagrams (CLD), stocks and flows, and agent-based modeling [54]. This section outlines the characteristics of each type (see a summary in Table 1), which will help us justify our choices in Section 3.2 based on the identified needs. Causal loop diagrams [30] (see Figure 1) depict relationships among variables within a system, helping to elucidate mental models and hypotheses without describing variable behavior over time [56]. Stock and flow diagrams (see Figure 1), on the other hand, illustrate temporal behavior through stocks, flows, and rates, often linked to mathematical models for simulation using tools like Stella [15], Vensim [19], and InsightMaker [22]. Agent-based modeling simulates system behavior by modeling individual agents' interactions based on predefined rules, focusing on emergent behaviors not anticipated by the model's designers [35]. The uncertainty inherent in social sciences often makes model predictions imprecise, regardless of the chosen modeling approach. However, dynamic models remain highly valuable as they provide an affordable playground for exploring the dynamics of complex systems and deriving insights [54].

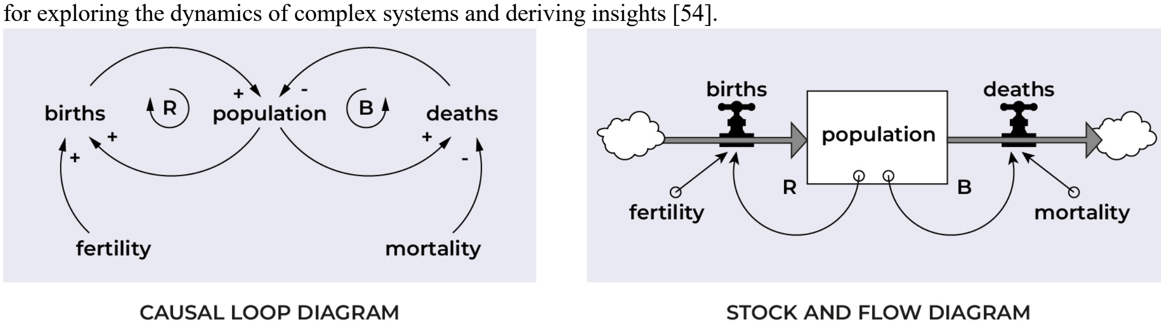

Figure 1: In a CLD, positive links (+) signify that if the cause increases, the effect increases, and vice versa. Conversely, negative links (-) indicate that if the cause increases, the effect decreases, and vice versa. Closed paths form feedback loops: reinforcing loops (R) amplify effects, like the birth loop; balancing loops (B) stabilize systems, like the death loop. Stocks represent accumulated resources (e.g., population), while flows denote inputs and outputs (e.g., births and deaths) at specified rates (e.g., fertility and mortality).

Table 1: Types of sociotechnical systems modeling.

	Causal loop diagrams	Stocks and flows	Agent-based modeling
Expression	Graphical	Mathematical	Computational
Time	Non-temporal	Temporal	Temporal
Unit	System	System	Individuals
Approach	Top-down	Top-down	Bottom-up
Use	Represent the relationships between variables, identify feedback loops	Simulate the behavior of a system, identify critical points	Simulate the behavior of a system, identify emergent behaviors

2.4 Systemic design methods

Systemic design [27] [51] is a new interdisciplinary field of research at the crossroads of systems thinking [3] [13] [40] and design thinking [11] [26] [59], which develops methods and tools to tackle complex, multi-scale problems at the social and sociotechnical level. Systemic designers generally embrace a highly qualitative approach, occasionally employing causal loop diagrams but rarely utilizing dynamic stock-and-flow models [7]. Systemic design is particularly relevant to our purpose as it integrates the systemic approach into the design process. The Systemic Design Toolkit [28] outlines a seven-stage methodology, depicted in Figure 2. However, the level of intervention by systemic designers differs from that of HCI designers. Indeed, unlike interaction designers which focus on product/service design, systemic designers primarily focus on organizational and political level [27], through the design of public policies, regulations, incentives, awareness-raising campaigns, etc.

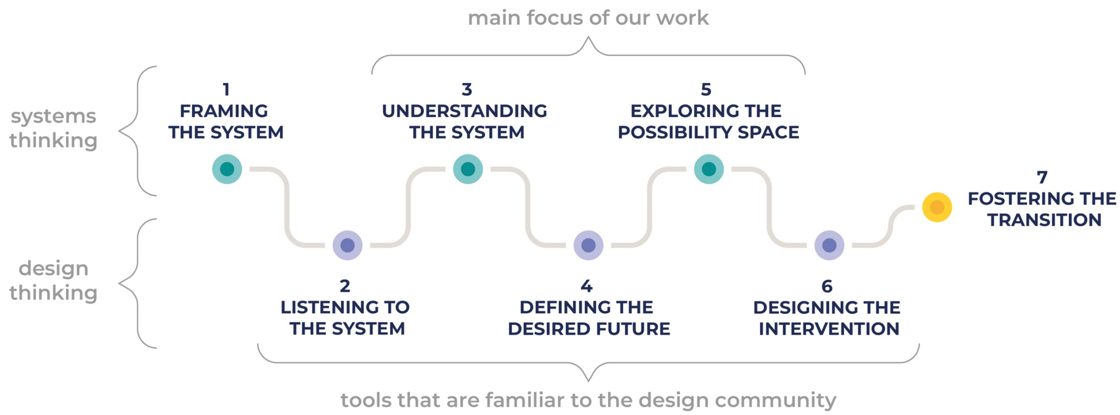

Figure 2: The seven stages of the systemic design process inspired by the Systemic Design Toolkit [28].

2.5 Meadows' leverage points

After modeling and understanding the dynamics of existing rebound effects, the goal is to develop strategies to mitigate these negative effects. System thinkers and systemic designers typically use the leverage points identified by Meadows [38] to influence the behavior of a complex system. These leverage points can be categorized into four groups (see Table 2), ranging from the easiest to activate, to the most difficult to activate but effective in the long term.

Table 2: Categories of leverage points [38] explained through the demographic example presented in Figure 1.

Category	Examples of leverage points
Acting on the constants and parameters of the system.	For the demographic example, this could be done by changing the initial population.
Acting on feedback loops and delays.	For example, it would mean changing the fertility or mortality rate, creating new feedback loops, or altering the time delay between changes in the population and changes in births or deaths.
Modifying information flows, changing system rules.	This can act at different levels of the diagram. For example, it could result in informing the population about medical risks, which could reduce the mortality rate, or implementing a birth policy that provides subsidies to large families and increases the birth rate, with a certain delay.
Changing the goals of the system or altering the underlying paradigm.	For example, the government could aim to limit climate change instead of maintaining economic growth. This would have an impact on its policies regarding birth rates. Similarly, individuals can shift paradigms, moving from a family-centered life to one focused on work or personal fulfillment.

2.6 Coverage of the related work

System dynamics can be used to describe the dynamics and orders of magnitude of rebound effects. Systemic design, on the other hand, proposes the integration of a systemic vision into a design process. Both are generally used for policy or strategic design, not for product or service design. To our knowledge, no previous studies have combined systemic design and system dynamics to explain rebound effects and test mitigation strategies on a concrete case study.

3 A prototype to explore the potential of systemic modeling

Our long-term objective is to provide designers with a methodology that enables them to identify existing rebound effects, understand their magnitude and compare the effects of various design mitigation strategies. We believe that systemic modeling and simulation, integrated into a design process, could offer a promising opportunity to meet these needs. In this study, we investigate designers' perceptions of collaborative modeling and examine how it could be integrated into the design process. After introducing the requirements and rationale, this section presents our systemic modeling methodological prototype. For the sake of a more pedagogical presentation, we illustrate our purpose using the example of a platform for second-hand clothing, which is the case study used in the workshops (see Section 4.1).

3.1 Requirements of the collaborative modeling methodology

Identifying the direct and indirect effects of an interactive system, as we briefly did in the Section 4.1 regarding the second-hand resale platform, is a first step towards designing a more sustainable platform. This could lead to the consideration of design ideas to limit adverse effects. However, it is not sufficient to support their mitigation. Indeed, systems dynamics often exhibit counterintuitive behaviors that are challenging for the human brain to grasp and anticipate [20]. Moreover, exploring the solution space is a challenge when designing for sociotechnical systems, because we cannot test the effects of a solution as directly as in design, through prototyping and user testing. Modeling and simulation could enable:

- Representing the direct and indirect effects of a product or service's design at a sociotechnical level.
- Quantifying the magnitudes of these effects over time.
- Exploring prospective scenarios and comparing design alternatives, which may combine multiple levers of action over time to address both the urgency of the situation and initiate more structural changes.

In line with Smaldino [54], we do not view dynamic modeling as a predictive tool, meant to forecast the most likely future. Instead, we employ it as a prospective tool, enabling reflection through the manipulation and exploration of potential futures. For example, in our case study, we could envision reintroducing the distance filter, proposing users to donate their clothing to charities under certain conditions, providing users with better information about the origin and journey of items for sale, or even rethinking the business model. These measures could be combined or implemented gradually over time. Simulation could facilitate a relative comparison of various design strategies. The prototype of the systemic modeling methodology that we are developing aims to facilitate collaborative thinking and decision-making among various stakeholders. For example, in this case study, users of this methodology would include designers, decision-makers, and engineers from the company that offers the platform, as well as fashion and textile industry experts. It could also be considered to integrate policymakers depending on the project's scope. The way to organize the project and involve stakeholders are among the aspects we wanted to investigate with the designers in these workshops.

3.2 Rationale: selecting the modeling technique and building the methodology

We aim to empower designers to understand and mitigate rebound effects, while gaining a better understanding of socio-technical system dynamics in general. Furthermore, given the uncertainties related to the future behaviors of users in a specific market (like that of second-hand clothing sales in our case study), it does not appear advisable to depend on an agent-based model to anticipate emergent phenomena. Therefore, we prefer to rely on scenarios generated by designers' imagination and their knowledge of users. Among the dynamic modeling techniques presented in the Section 2.3, it appeared more relevant to base our modeling approach on the construction of a stock and flow system dynamics model. Its top-down approach avoids the "black box" effect of agent-based modeling and could enable designers to have an overview, become familiar with system dynamics, and describe anticipated emergent phenomena. However, stock and flow diagrams are relatively challenging for individuals who are not experts in system dynamics, while causal loop diagrams have been widely embraced by systemic designers due to their straightforward formalism. For this reason, we opted to draw inspiration from the simplicity of causal loop diagrams and the calculation principles of stock-and-flow modeling. We suggest initially creating an influence diagram, a simplified version of causal loop diagrams that does not impose polarity on causal arrows, as we provide a more precise description of their nature later in the process. Then, we dismissed generic system dynamics tools (see Section 2.3) and developed a specific prospective modeling prototype[1] [8]

[1] The tool and its description can be found here: https://lii.enac.fr/projects/magnitude/

that requires minimal or no coding and which formalism is closed to CLD. Regarding the methodology, we relied on the methodological framework of group model building (see Section 2.3). However, the practical implementation of this methodology can vary greatly depending on the projects [50]. Furthermore, this methodology does not integrate with a design process. Therefore, we also drew inspiration from the process proposed by the Systemic Design Toolkit [28] and by the Systemic Design Group in Berlin [57], which describes a modeling methodology for causal loop diagrams. In short, we have enhanced this latter process by adding stages for defining the data collection strategy, quantifying influences, building scenarios and models, and monitoring effects.

3.3 Resulting collaborative modeling process

The resulting systemic modeling prototype is both qualitative and quantitative, as it involves first creating a qualitative understanding of the situation and then employing mixed method data collection [1], that combine qualitative and quantitative techniques, to produce a quantified model that can be simulated. This model is designed to represent orders of magnitude and trends in order to draw qualitative conclusions (by relatively comparing alternatives). The entire process, described in Table 3, is iterative in nature, allowing for continuous refinement.

Table 3: Description of the modeling methodology steps through the example of the Vinted case study.

Modeling methodology steps	Description
Framing	Formation of the core project team, bringing together various disciplines within the organization, including technical, design, and strategic expertise. Identification of the project's values and scope.
Preliminary investigation	Preliminary investigation of the platform's effects based on existing data (e.g. scientific and press articles describing the direct and indirect effects of Vinted platform).
Identification of variables	Expansion of the project team to include external experts, such as researchers who have studied behavior on second-hand platforms, environmental economists, and policymakers. Collective identification of key variables of interest, such as GHG emissions, quantity of clothing donated to charitable organizations, etc., as well as the variables that may influence them, such as number of garments sold, number of users, revenue generated by sales.
Initiation of the influence diagram (qualitative)	Collective development of an initial version of the diagram, representing the influences among these different variables (see a simplified example in Figure 3).
Consolidation of the influence diagram (quantitative)	Identification of data collection methods to quantify the influences and anticipate the potential effects of a new design. Depending on the types of influences, it is possible to: rely on existing studies (e.g., to determine eqCO2 emissions per kilometer traveled), utilize available quantitative data measured by the platform (e.g., to understand the average percentage of income from sales used to purchase other second-hand clothes on the platform), conduct specific studies with users regarding current practices and/or the potential effects of a new design on future practices, including possible new rebound effects (using conventional techniques such as observations, interviews, and quantitative surveys), or make assumptions based on expert opinions. These assumptions can lead to the creation of several scenarios (e.g., optimistic and pessimistic).
Construction of a dynamic modeling (quantitative)	Iterative development of a quantitative dynamic model using an interactive modeling tool (see Figure 4). Due to the inherent uncertainty in social phenomena, several versions of the model can be created to represent multiple possible scenarios (e.g., optimistic and pessimistic).
Ideation on design strategies to mitigate the rebound effects	Ideation on how to reduce rebound effects by redesigning the platform, service, and/or business model. Production of model versions to represent design alternatives (potentially including the progressive implementation of multiple measures over time) for each scenario. Ideation can draw inspiration from variables, influence diagram, prospective model, and should address different leverage points' categories (see Section 2.5).
Simulation for comparing design strategies	Simulation of models and relative comparison of design alternatives (see Figure 4) to collectively define a strategy at different levels (design, services, strategy), potentially involving other stakeholders such as users or impacted actants (e.g., charitable organizations). The relevance of the results depends on the construction of the model. However, the stakeholders are aware of the model's limitations, given their active involvement in its development.
Effects monitoring	Observation of the effects of these measures over time, comparing them with the envisioned

Modeling methodology steps	Description
	scenarios, and iterating on the strategy and model based on observed discrepancies.

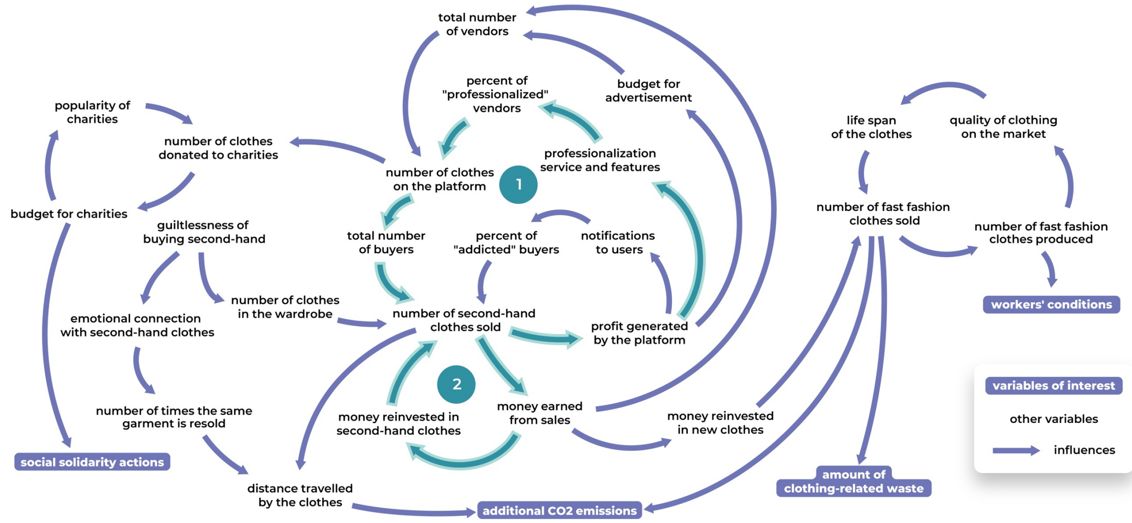

Figure 3: Simplified example of an influence diagram representing the second-hand clothing sales platform effects (case study described in Section 4.1). Loop (1) shows that the number of garments sold impacts sellers' earnings, which in turn affects reinvestment in the platform, subsequently influencing sales. Loop (2) demonstrates that sales influence platform earnings, which impact resources for professionalization services, affecting the percentage of professionalized sellers, and consequently, platform activity and sales.

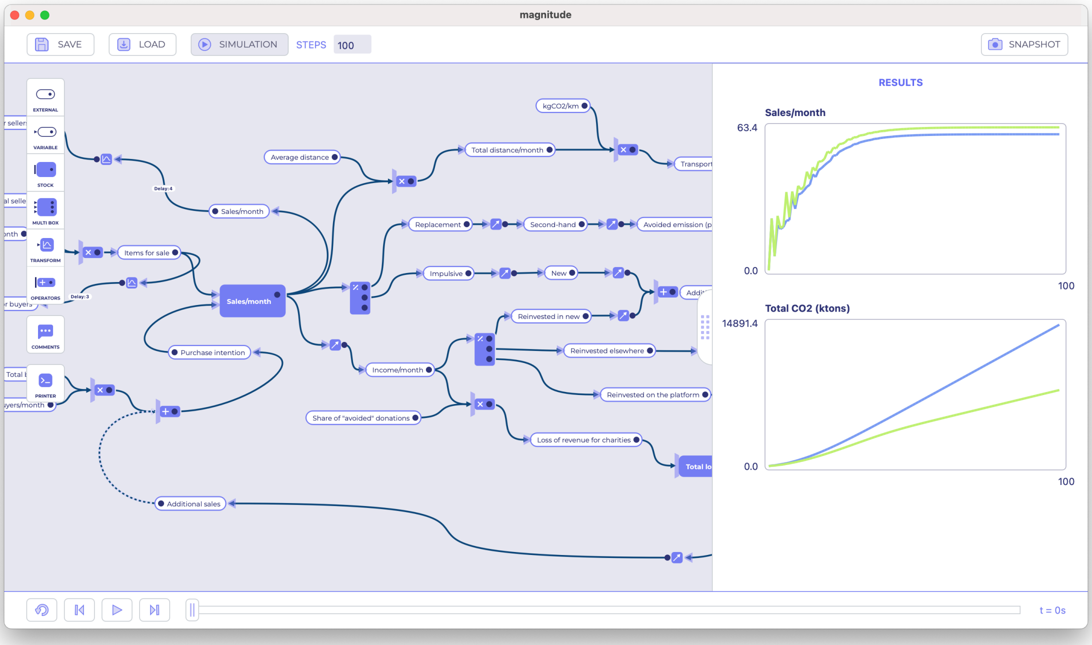

Figure 4: **Example of a dynamic model and a simulation comparing design strategies using the interactive modeling tool [8].**

4 Study

We aim to explore the potential of collaborative modeling and simulation, to determine how it can be integrated into a design process, and to collect the perceptions and needs of designers. To this end, we engaged professional designers in a practical case using our methodological prototype in two workshops. This section introduces the case study and outlines the study conditions.

4.1 Case study: a second-hand clothing resale platform

Rebound effects are often generated when a digital product or service is deployed on a massive scale to the public. This is especially applicable to gig-economy platforms like Airbnb, Uber, Deliveroo, Blablacar, and Vinted. For our case study, we selected Vinted as the subject, as it was the focus of a comprehensive study [58] on user behavior in 2021 (350,000 users surveyed). However, the aim of our study is to assess the relevance of a systemic modeling methodology to represent and understand the effects of consumption behavior at the scale of a socio-technical system. If we assume that these behaviors can be modeled with a consequential approach, regardless of the patterns, then the results of our study could be generalized to any type of product/service/technology used on a large scale.
Table 4 describes some of the direct and indirect effects generated by the Vinted platform. The platform's design can influence user behavior and cause rebound effects. For example, the platform sends notifications to encourage increased purchases, provides professionalization services to sellers through virtual stores, and uses algorithms that prioritize sellers with higher sales, making occasional sellers less visible [29]. Notably, the platform removed the filter feature that allowed buyers to search for items near their location [42], thereby restricting local hand-to-hand transactions. As a result, the clothes sold now travel greater distances, leading to increased carbon emissions.

Table 4: **Some of the direct and indirect effects of the second-hand clothing resale platform.**

Type of effect	Description
direct effects	Carbon emissions resulting from the company, platform, and transportation of sold clothes [58].
indirect effects / direct rebound	Impulsive purchases account for at least 25% of transactions on the platform [58]. Furthermore, the lower prices of second-hand items enable some buyers to purchase more articles [12].
indirect effects / indirect rebound	The clothing sold on this platform is largely sourced from fast fashion and is often lightly worn [29] [33]. By facilitating their resale, the platform provides purchasing power to the sellers, who reinvest it partly outside the platform, in new items, including brand-new clothes [58].
indirect effects / systemic rebound	The platform assists sellers in transitioning towards a quasi-professional practice, notably through the creation of a virtual store. This changes their relationship with clothing consumption. Juge [29] characterizes the users of this new practice as "consu-merchants". Furthermore, the platform induces systemic changes in the perception of clothing and used garments, leading to a decrease in clothing donations to charities. The increasing number of users on second-hand clothing resale platforms are now less inclined to donate garments they can sell. This has a negative impact on the budgets of charitable organizations, resulting in reduced visibility and hindered social initiatives in the long term [47].

4.2 Methodology

We conducted two workshops with professional designers to empirically investigate their perceptions of collaborative systemic modeling and its role in addressing rebound effects. During each of these two workshops, the designers were invited to work on the same case study of a second-hand clothing platform (described in Section 4.1). Each workshop involved five professional designers, for a total of ten participants. The workshops were conducted remotely in French over a half-day.

4.2.1 *Participants.*

The recruitment of participants was carried out by posting an announcement offering a "workshop on sustainable systemic design" on the Flupa network, the French-speaking association for user experience professionals, and by sharing the announcement within the network of former collaborators affiliated with our research laboratory. Among the ten participants, six identified as women, and four as men (see Table 5).

Table 5: **Workshops and interviews participants.**

ID	Professional interest in sustainability	Degree of familiarity with systemic design	Workshop	Group	Interview
D1	no	no prior knowledge	1	A	yes
D2	role related to sustainability	no prior knowledge	1	A	no
D3	no	no prior knowledge	1	B	yes
D4	no	no prior knowledge	1	B	yes
D5	no	had heard about it, no practice	1	B	yes
D6	focus of some client projects	had heard about it, no practice	2	C	no
D7	no	no prior knowledge	2	C	no
D8	focus of some client projects	no prior knowledge	2	D	no
D9	focus of some client projects	had heard about it, no practice	2	D	no
D10	role related to sustainability	had read about it and seen CLD, no practice	2	D	no

4.2.2 *Tools.*

The workshops and semi-structured interviews were conducted via video conferencing and recorded using the Teams platform [62]. During the workshops, participants engaged in a dynamic collaborative process utilizing a Miro board [61]. The potential of modeling and simulation was illustrated by the introduction of the prospective modeling prototype[2] that we developed for the purpose of consequential modeling of sociotechnical behaviors [8].

[2] The tool and its description can be found here: https://lii.enac.fr/projects/magnitude/

4.2.3 *Outline of the workshops.*

Table 6: Workshops steps.

Workshops steps	Description
Preliminary investigation prior to the workshop	Participants were asked to read a 2 pages summary of press articles highlighting some direct and indirect effects of Vinted platform. Based on this reading, the participants prepared a representation of their understanding of the situation, and generated an initial list of design ideas to mitigate the rebound effects. Although two participants were unable to complete this task, we received an additional representation from a designer (D11) registered for the second workshop, who ultimately could not attend, resulting in a total of nine representations.
Spontaneous representations	During the workshop, each participant presented their schema to the others, explaining their representation choices regarding organization, emphasis, connections, etc. (see Figure 7 and Figure 8).
Introduction to systemic design and the modeling approach	The workshop facilitator provided a brief presentation on the fundamentals of systems thinking, systemic design, intervention points within a system as described by Donella Meadows [38], and Causal Loop Diagrams [30], as well as the concept of variables and the key phases of the workshop.
Identification of variables	Participants engaged in a collaborative ideation session to identify the variables that describe the situation, based on the comprehensive document they had read (see Figure 5).
Initiation of the influence diagram (qualitative)	Participants were divided into two groups and tasked with constructing an initial version of the influence diagram, delineating the relationships between variables using arrows to represent the influences from one variable to another (see Figure 6).
Consolidation of the influence diagram (quantitative)	Continuing in their respective groups, participants initiated the process of proposing methods for quantifying each arrow or collecting data to enable quantification in comment bubbles on the diagram (see Figure 6). Moreover, they were encouraged to use this opportunity to iteratively refine the diagram.
Presentation of the diagram to the other group	Each group presented their respective diagram to the other group, elucidating the inquiries they posed, and the challenges encountered during its production.
Demonstration of dynamic modeling and simulation	A simplified quantitative model was presented to them, and was simulated using our interactive modeling tool [8], providing them with an overview of the simulation's potential.
Ideation on the design	The participants engaged in a short ideation session, assuming the roles of hired UX designers for the platform who were tasked by the new management to propose ideas aimed at mitigating the rebound effects. They were invited to draw inspiration from the variables, influence diagram, prospective model, as well as from Meadows' leverage points (see Section 2.5).
Discussion	Lastly, a discussion allowed participants to express their perception of the contributions, limitations, challenges, usability of each step, as well as their overall perception of the approach and its feasibility.

The workshops aimed to familiarize professional designers with the collaborative systemic modeling methodological prototype through hands-on experience. The goal was to gather insights about their perception of this methodology and its possible integration into a design process through observation and discussion. We also sought to measure their grasp of fundamental concepts such as variables, causality, modeling, and quantification. Given that this methodology applied to a real case might span several weeks or even months, we had to provide a comprehensive overview within the time constraints of the workshop (see Table 6). To achieve this, we requested professional designers to complete preparatory work prior to the workshop (see Table 6). During the workshop, we briefly engaged them in the key stages leading up to quantitative modeling, and subsequently presented an exemplar of a simplified dynamic model. Finally, we gathered their feedback through a semi-structured discussion. For the first workshop, due to some participants' time constraints, this took the form of a brief discussion at the end of the workshop, followed by semi-structured individual interviews for those who wished to pursue the discussion further (four out of five designers). During the second workshop, participants wrote their feedback on sticky notes that they placed on areas of the Miro board (general approach, variable identification, diagram, dynamic modeling, project in real context), divided into feedback categories (potential contributions, limitations, feedback/advice, and usability). A collective discussion followed, based on the sticky notes.

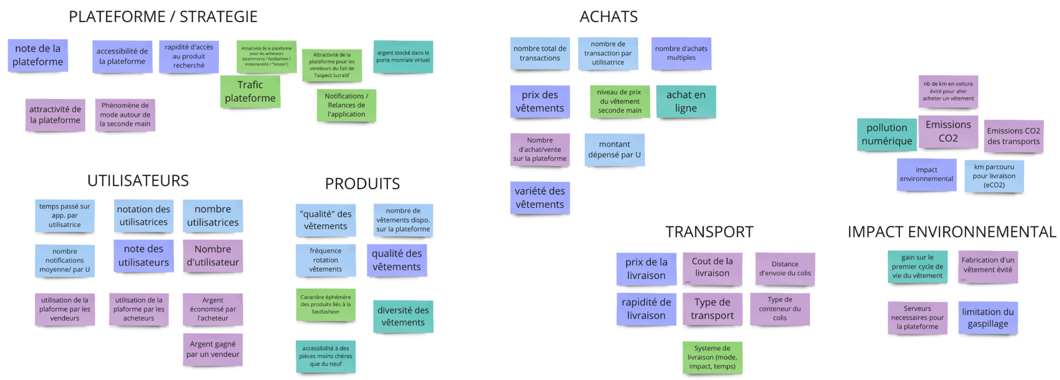

Figure 5: Screenshot of the variables identified by participants on Miro, group by categories: platform strategy, users, products, purchases, transportation, environmental impact.

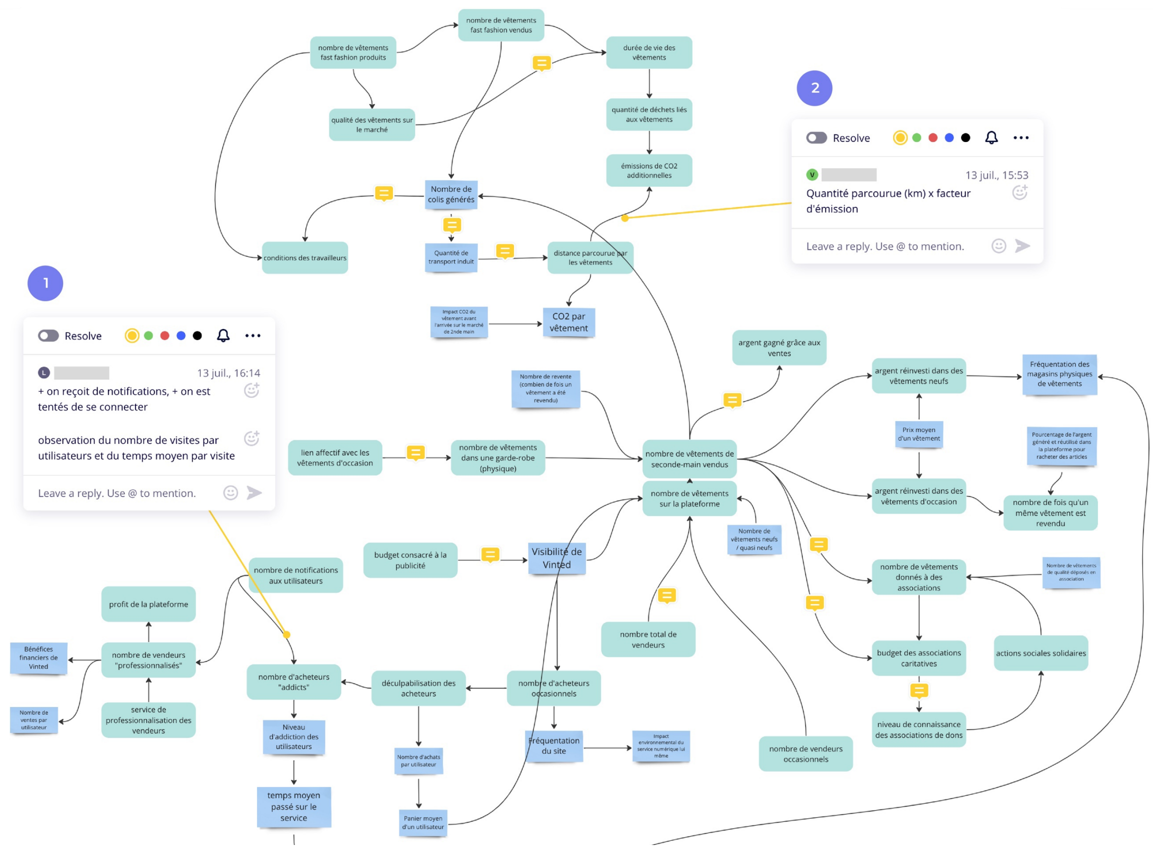

Figure 6: Screenshot of an influence diagram (quantitative) produced by the participants on the Miro board. Participants commented on various arrows (influences) by indicating how to quantify them. For example, (1) explains that, to understand the link between the number of notifications and the number of "addict" buyers, one could observe the number of visits per user and the average time per visit. In the comment (2), it is indicated that

to calculate the additional CO_2 emissions related to transportation, one needs to multiply the total distance traveled (in km) by the emission factor.

4.2.4 *Analysis.*

To derive the conclusions presented in the Section 5, our analysis drew upon not only the investigation of post-workshop reflective discussions (including semi-structured interviews) but also a classification of the designers' interventions, exchanges, and actions throughout the various stages of the methodology. To achieve this qualitative content analysis [17], we transcribed all the workshops and interviews, and for each one, we systematically highlighted important elements by category: design ideas discussed before and during the workshop, remarks and questions of interest (including misunderstandings and challenges), and the contributions and limitations of the methodology, particularly in terms of design implications, usability, and feasibility. Subsequently, we grouped the excerpts from both workshops and the four interviews by category and synthesized the main findings.

5 Study results

This section presents the principal findings of the study. Given the qualitative nature of the study, the objective is to describe and interpret the workshop activities and discussions in order to formulate hypotheses for future research.

5.1 Spontaneous schematic representations

Prior to the workshop, most participants spontaneously expressed their understanding using heuristic and causal diagrams. This allows us to posit that causal loop diagrams are well-suited for qualitatively representing systemic situations that involve direct and indirect effects. Among the nine schematic representations, eight are diagrams, employing texts and connections, and one is a categorization of notes (D5). Within the eight diagrams, four (D1, D7, D10, D11) represent causal links (see Figure 7). The other four representations (D3, D6, D8, D9) represent both causal and heuristic links (see Figure 8).

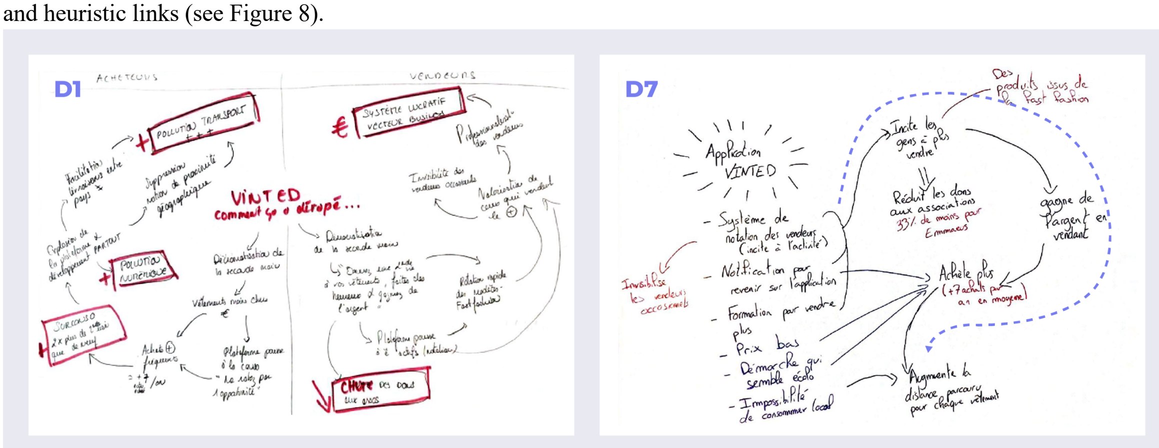

Figure 7: **Spontaneous schematic representations – causal links. One of the causal pathways described by D7 (on the right): sellers rating system, notifications, and professionalization services -> encourage users to sell more -> users earn more money -> users buy more -> increase in distance traveled.**

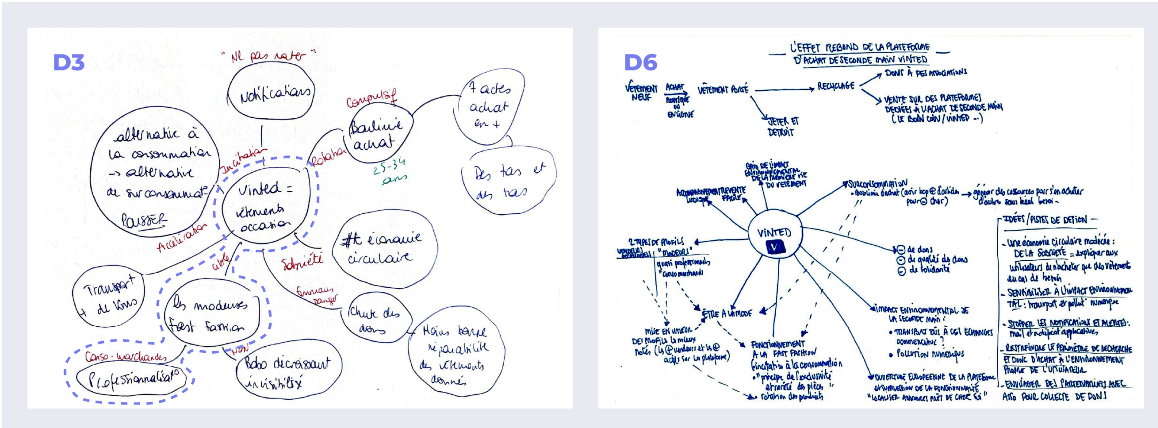

Figure 8: Spontaneous schematic representations – causal and heuristic links. A heuristic pathway described by D3 (on the left): the platform –(targets)- fashion addicts –(consumer-merchants)- professionalization.

5.2 Perspectives of the participants regarding their role

Professional designers who participated in the workshops collectively expressed their aspirations and efforts to have a positive impact on the environment and society through their design practices. Notably, three designers (D6, D9, D10) spontaneously mentioned, during their introductions, the transformative power of design beyond the realm of digital products, influencing societal lifestyles on a broader scale. For instance, designer D9 stated, "*[I] firmly believe in the social and societal significance of design, questioning perceptions, lifestyles, and transforming societies*". This indicates that some designers are willing to take responsibility for limiting rebound effects, suggesting that there could be future users of a methodology that addresses these effects.

5.3 Main ideas generated during the workshops

One of our objectives was to evaluate the impact of the modeling methodology on the production of design ideas to mitigate the identified rebound effects. Table 7 presents the main design ideas proposed by participants before the workshops and during the workshops, after the collaborative modeling. Six out of ten designers generated new ideas following the modeling exercise. However, out of the 23 ideas generated during the workshops, only three were completely original, meaning they had not been previously imagined by any designer before the workshops. The description of the rebound effects prior to the workshop was enough for the designers to collectively generate most of the ideas. Interestingly, after applying the systemic modeling methodology, certain ideas were presented in combination for greater impact. For example, designer D1 suggested assigning an environmental rating to clothing and imposing an annual quota on users based on this rating. Users exceeding the quota would be redirected to donations. It appears that modeling is less about generating ideas and more about refining, completing and combining them. Finally, although the ideas cover different levels of leverage points, 13 out of 23 directly relate to the design of the platform's interface. This suggests that product designers, service designers, and strategy decision makers should all be involved in this process.

Table 7: Main ideas generated during the workshops. The ideas are grouped by category of leverage points (see Section 2.5). Ideas that directly impact the platform's design are highlighted in bold. The right-hand columns indicate the ID of the designer(s) who suggested each idea. Suggestions to remove "dark patterns" (e.g. notifications to users, algorithms that favor large sellers, etc.) from the current design have been excluded since they are not original design ideas.

Category of leverage points	Ideas	Before the workshops	New ideas after modeling
Acting on the constants and parameters of the system.	Using a more environmentally friendly parcel transport system.	D4, D7	D8
	Providing local sales/collection points to reduce transportation.	D6, D8, D10	D3
	Promoting shared transport (bulk purchases by multiple buyers).	D8, D9	
Acting on feedback loops and delays.	**Implementing a point-based system (gamification)** that rewards users' eco-friendly behaviors (selling eco-designed clothing, buying locally).	D4, D5	D1, D3
	Redirecting users to donate to charitable organizations (if the clothing doesn't sell, if the user has reached their quota, etc.).	D1, D10	D3, D6, D9
	Donating a portion of the profits to charities.	D8, D9	
	Offering users low-carbon ways to spend the money they have saved.		D2
	Introducing a local virtual currency within the app that requires users to reuse their earnings on second-hand items.	D7	
Modifying information flows, changing system rules.	**Informing users about the environmental cost** of clothing.	D1, D6, D8, D9	D3
	Highlighting users with virtuous behaviors (e.g., responsible seller badge) rather than emphasizing the number of sales.	D8	D9
	Tracking clothing to determine how many times they have been resold on the platform and the distance they have traveled.		D1
	Imposing quotas on users (maximum number of purchases/sales per year).	D1, D7, D8	D3
	Limiting results by geographical proximity.	D7, D9, D10	D6, D8
	Banning certain non-environmentally friendly brands (fast fashion).	D8	
	Implementing a prevention system against addictive behaviors.	D8	
	Lobbying the government to establish a national carbon quota related to clothing consumption.	D7	
Changing the goals of the system or altering the underlying paradigm.	**Promoting clothing repair and customization** (tutorials, badges).	D5	D2
	First gathering user needs, then displaying a limited set of corresponding results (to avoid pushing overconsumption with an endless list of items).	D5	
	Enabling clothing exchange.	D8, D10	
	Encouraging users to reduce the number of items in their wardrobes (e.g., by showing how to wear the same clothing item throughout the year).		D8, D10
	Changing the advertising message (promoting responsible consumption, donations, rather than savings).	D3	D5, D6
	Partnering with local public entities to educate on sustainable consumption practices.	D9	
	Organizing local events in collaboration with associations.	D2, D9	

5.4 The potential contributions of the modeling methodology throughout a design process

To examine how the steps of collaborative modeling methodology could contribute to and integrate into a design process, we present in Table 8 our observations and user feedback for each typical design activity: Discovery (research), Interpretation (synthesis and problem definition), Ideation, Experimentation (prototyping and testing), Evolution [59]. In particular, we observed that, although ideation began in the minds of participants during preliminary research, it could be effectively shared, debated, structured and completed on the initial diagram, then challenged and refined on the consolidated diagram. The implementation of all of these individual ideas would likely result in the platform becoming excessively restrictive. The participants combined ideas to form design strategies (see Section 5.3), but they were unable to compare alternative strategies. We propose that stakeholders compare the impact of these design strategies through simulation. The selected strategies could be prototyped and tested in real life. Depending on the insights obtained, a new phase of ideation and simulation may take place to refine the design strategies envisioned. Finally, the simulation could be compared to observed effects (monitoring), and discrepancies could lead to adjustments in the dynamic model or design iterations. A proposal for the integration of systemic collaborative modeling is presented in Figure 9.

Table 8: Contributions of the modeling methodology as observed and perceived by participants.

Modeling methodology steps	Design stages	Contributions perceived
Preliminary investigation	Discovery	Helps building a first knowledge about the existing direct and indirect effects, with a systemic lens, and allows a "*better understanding of the subject, its magnitude, its implications*" (D7).
	Ideation	Some first ideas of mitigation might emerge while investigating.
Identification of variables	Discovery	Helps collectively identifying a broader vision of the direct and indirect effects.
	Interpretation	Helps collectively defining the goals (e.g. reduce CO_2 emissions).
	Ideation	May generate novel ideas that relate to these impacts and goals.
Initiation of the influence diagram (qualitative)	Discovery	Helps discovering influences that were not obvious, and "*gain[ing] a broader perspective*" through "*a highly effective visualization*" (D6).
	Interpretation	Helps building a collective vision of the current situation and communicating this to the stakeholders in a "*quite clear and straightforward*" (D4) manner.
	Ideation	Helps structuring the first design ideas to mitigate the rebound effects, visualizing what they could impact in the system, identifying unaddressed points and generating novel ideas that relate to influences and feedback loops.
Consolidation of the influence diagram (quantitative)	Discovery	Defining a detailed data collection method to quantify the influences helps delving deeper into the subject and raising more precise questions. The designers believed they would gain in-depth knowledge of the situation by looking for the "*real data*" (D1).
	Ideation	Quantification could lead to a refinement of ideas or the generation of new ones, following the new questions that have been raised (for example, tracking clothes and displaying the distance they have traveled).
Construction of a dynamic modeling (quantitative) and simulation for comparing design strategies	Interpretation	Scenarios help building a collective vision of possible future situations and communicate it to the stakeholders.
	Experimentation	Simulation makes the ideation tangible, it could help visualize the impacts, compare design alternatives over time, prioritize work axes.
	Evolution	Could lend more weight and legitimacy to communicate with the stakeholders and enable action. Could help monitoring the effects in a dynamic and iterative fashion.

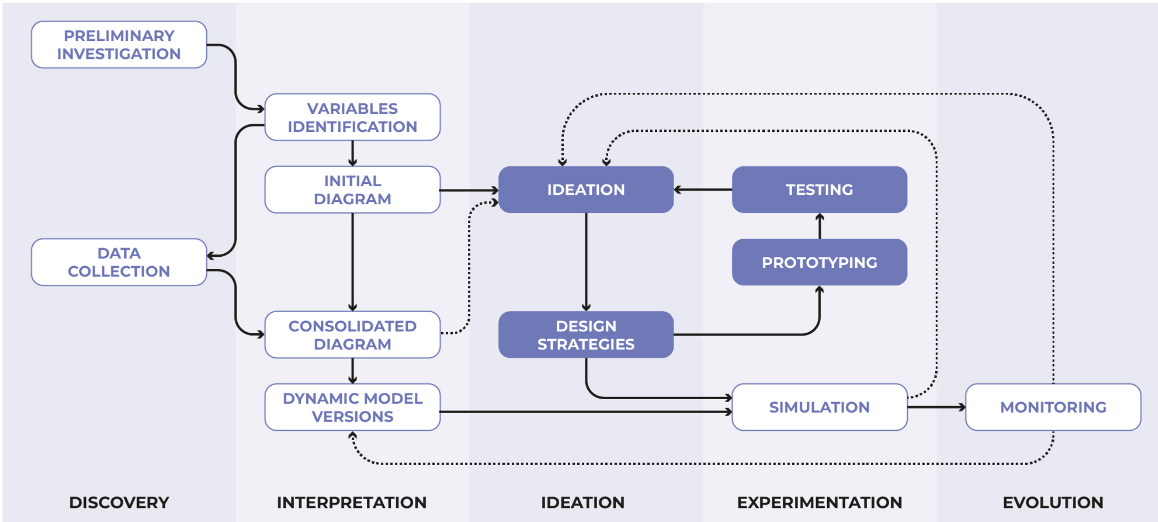

Figure 9: Proposal for integrating a collaborative modeling methodology into a design process, based on the workshop results. The activities related to the level of the sociotechnical system (second-hand market) are represented with outlined rectangles, while the activities related to the design (platform design, service design, and organizational design) are represented with solid rectangles. The process is seen as highly iterative but, for the sake of clarity, we did not represent the possible refinement of the initial diagram and variables according to the data collected, nor the progressive emergence of ideas coming from the preliminary investigation and the variables identification.

5.5 The perception of the participants regarding the quantitative aspect of this methodology

Nine out of ten participants were firmly convinced of the relevance and value of the quantitative aspect of this methodology for simulation purposes. For instance, D8 mentioned that quantification is particularly suitable for projects with environmental objectives: "*Regarding modeling and [simulation], I find it really interesting because it allows us to concretely visualize the impact of actions and compare situations. It reminds me of projects with clients we work on, especially those related to environmental considerations, where indeed, they want to quantify and measure, that's the transition to action*."

However, as indicated by D1 during the workshop, designers may not necessarily be accustomed to this type of exercise: "*[We, designers,] may be less familiar with quantitative tools.*" Therefore, we observed their reactions and questioned them about their perceptions of quantification. Two designers (D4 and D7) demonstrated great comfort and quickly posed specific and relevant questions, three designers seemed confident (D2, D9, D10), and four designers (D1, D3, D6, D8) expressed that the quantitative consolidation of the diagram presented challenges (summarized in Table 9). However, they extensively expressed their enthusiasm regarding the many benefits of quantification (see Section 5.4), and they appeared confident that rapid skill development could be achieved through practice.

On the other hand, designer 5 was more skeptical regarding dynamic quantitative modeling and raised several points of concern. For instance, the apprehension that the quantitative aspect might lead designers to solely focus on what can be quantified, potentially overlooking other important factors. Furthermore, designer D5 mentioned the risk of the methodology being misused for "*greenwashing*", by constructing an unrealistic and overly favorable model, that would be particularly effective as "*people are very confident in numbers.*"

Table 9: Difficulties experienced by designers regarding modeling and quantification.

Modeling methodology steps	Difficulties experienced
Identification of variables	Selecting the granularity level of certain variables (D1, D4, D5, D6, D7, D8). Defining the scope: which variables should be represented (D3).
Initiation of the influence diagram (qualitative)	Structuring the diagram to rationalize influences and avoid redundancies (D6, D7).
Consolidation of the influence diagram (quantitative)	Identifying a data collection source to quantify certain influences (D1, D3, D6, D8). Arbitrating between post-its and quantification comments to position exogenous variables, such as CO_2/km for transportation (D5).

5.6 Exploring the feasibility of this approach in a professional context

During the discussion on feasibility, some designers (D1, D3, D4, D5) raised the point that this approach requires time and resources, as well as access to data, which is only possible with strong support from the management. They mentioned that while they were unable to envisage implementing this methodology at the present time, they perceived a shift in dynamics within their organizations, with an increasing importance being placed on sustainability. In the immediate future, they believe that this approach could be more easily implemented on projects within the context of public markets that require commitments in terms of ecological impact (D5). On the other hand, after the workshop, designers D6 and D8 were determined to apply the discussed tools. D8 expressed, "*The use of this approach is sparking something in me to maybe take some time to revisit this approach on certain projects*," and D6 remarked, "*I believe there are things we can put into practice right away, and we leave [the workshop] with tangible tools*." In the professional realm, participants noted that implementing this approach aligns with designers' skill sets, given proper training or support. It would involve coordinating a multidisciplinary team comprising decision-makers, environmental specialists, designers, product managers, and technical experts.

6 Discussion

This section discusses the limitations of the study, the contribution of the methodology, and identifies new research perspectives to further this promising direction.

6.1 Limitations of the study

The workshop results indicate that the systemic modeling methodology is promising, as it can be integrated into a design process and assist designers in understanding rebound effects as well as in developing and comparing strategies to mitigate these effects through design. However, it should be noted that the 10 participants (all French) volunteered for the workshops, which may introduce a recruitment bias. In addition, these workshops aimed to gather insights from the pivotal role of the designer, but did not include the recommended diversity of stakeholders according to the methodology. It is likely that there will be more frictions under real conditions. We used a real case study with actual data. However, due to the limited time frame of the exercise, we only relied on data from the literature. This means that the consolidation of the diagram through a specific investigation has not been explored. Finally, we used only the modeling types that seemed most relevant for static modeling (influence diagram) and for dynamic modeling (based on stocks and flows). We hope that future research can complement our findings by involving more diverse participants, comparing other modeling types, and applying a collaborative modeling methodology to several real case studies on larger time scales.

6.2 Some key inputs from systemic approaches to Systemic Sustainable HCI

This paper initiates a new research area, which we propose to title Systemic Sustainable HCI. The objective of this research is to build on systemic concepts and tools to concretely support Sustainable HCI efforts. The systemic principles and tools that are explored through our prototypical systemic modeling methodology are the group model building process [2], the systemic design process [28], causal loop diagrams [30], system dynamics modeling [56], and Donella Meadows' leverage points [38]. The group model building process facilitates the construction of a shared vision among participants, an in-depth understanding of dynamics and causality, and a critical analysis of the models produced in support of decision-making. The integration of group model building into a design process was inspired by the main stages of the systemic design process, and has been refined through the workshops. Influence diagrams, which were inspired by causal loop diagrams, enabled designers to situate, structure, and complete their ideas for intervention. The use of leverage point categories facilitated the expansion of thinking to encompass a range of intervention levels and temporal scales. System dynamics modeling and simulation were perceived as highly promising for decision-making, as they allowed for the combination of multiple ideas into design strategies and the comparison of the magnitude of their impacts. Although still in its nascent stages and in need of further development, the systemic modeling methodology appears to align with Bremer et al's calls [10] for the provision of tangible tools to practitioners and for the addressing of both the urgency of the situation and the long-term. Other tools that are employed in the field of systemic design could prove beneficial in the sustainable design of interactive systems. Further research is necessary to investigate the potential of these tools and to adapt them to the specific requirements of interactive system design, as outlined in section 6.4.

6.3 Systemic modeling methodology scope

The fact that this methodology integrates well into a design process and is perceived as useful by designers for understanding rebound effects and comparing design strategies does not guarantee that rebound effects will be effectively reduced, let alone to what extent. This is simply impossible due to the nature of rebound effects and the complexity of social phenomena. The most we can do is to provide designers with a tool to help them make decisions, with a level of precision that meets their needs. If necessary, the accuracy with which existing rebound effects are represented in the model can also be verified by external validation (using tools such as [48]), i.e., by comparing simulated and historical real data. Furthermore, the proposed methodology does not provide a means to anticipate unprecedented rebound effects, which may be caused by the new design (discussed in Section 6.4). Additionally, as one participant pointed out, the risks of misuse and greenwashing must not be overlooked. Systemic modeling methodology is not designed to generate numerical results for claim purposes, but rather to inform design and strategic choices. It is important to ensure that stakeholders are diverse and representative to confer a certain level of robustness to the methodology.

One may also question the realism of this approach, that is, whether Vinted would be willing to implement rebound effect mitigation strategies that may result in the loss of users, transactions, and money. Firstly, it should be noted that 20% of Vinted users declare using the platform primarily for ecological reasons [58]. This results in 16 million users out of the 80 million total users in 2021. It appears feasible to lose some users and retain those with ecological convictions and survive by changing the business model. This could be achieved through a logic of donations, subsidies, or annual subscriptions. Secondly, we invite our readers to imagine a future (hopefully near) where the current economic model will be questioned, as claimed by [52]. There are already models that prioritize criteria other than money in their strategic decisions, such as cooperative organizations and mission-driven companies [34].

6.4 Research opportunities

A narrative foundation as the cornerstone of the methodology. As mentioned by a designer, it is important to ensure that the quantitative aspect does not overshadow the qualitative aspect, which provides a more comprehensive view of the situation and allows for the inclusion of certain non-quantifiable elements, such as systemic rebounds and societal impacts. A narrative support could bring together the qualitative and dynamic models during the definition and comparison of design strategies. Thus, scenario exploration could start at the beginning of the methodology, and these scenarios could evolve and refine throughout the process.

Scenario exploration and values-based decision-making. Future studies could be explored to support the construction of possible future scenarios and trajectories to reach them. Moreover, it is important to acknowledge that the process of decision-making is contingent upon the prioritization of impacts, which are inherently multifaceted and may necessitate trade-offs. This prioritization is influenced by the values of stakeholders. Value-oriented design approaches can assist in the explicit articulation of these values.

A more in-depth comprehension of the digital rebound effects. The outcomes of the proposed systemic modeling methodology and subsequent decisions made are contingent upon the initial assumptions and identified rebound effects. It is therefore of the utmost importance to expand and reinforce research into rebound effects associated with digital products and services, particularly within the domains of social sciences and psychology.

Best practices and resources to facilitate quantitative modeling. Quantitative modeling can be challenging for stakeholders who are not familiar with it (see Section 5.5). There is a need to develop best practices and resources to facilitate each step.

A modeling tool tailored for rebound effects. In order to enable non-experts in system dynamics to engage in the construction of a quantitative model and scenarios, it would be useful to provide a modeling tool tailored to the needs of modeling sociotechnical systems and rebound effects (e.g. describing consumption patterns, representing uncertainty, facilitating scenario comparison, version management, etc.).

A tool for ideation on rebound effects caused by mitigation measures. In these workshops, we focused on understanding existing rebound effects, mitigating them through design, and anticipating associated impacts. However, the new design, conceived to mitigate the observed rebound effects, could itself lead to unforeseen new rebound effects. Prospective modeling could simulate these effects over time, provided they are identified, and their magnitudes estimated. The prototyping and testing phase described in Section 5.4 could help identify them. Nevertheless, it could be highly beneficial to provide designers with ideation tools to envision the possible effects during the ideation phase so that they could address them during the design evaluation.

Prospective modeling. To help quantify the magnitudes of the rebound effects (data collection step in Section 3.3), it would be interesting to work on prospective data collection methods, for example, by studying the feasibility of surveying users on their future practices (prospective survey) or exploring other opportunities.

Involving policy makers in the collaborative modeling. An effective approach to mitigate undesirable rebound effects is to intervene on multiple levels, particularly at the policy level [10], through regulatory measures. An interesting research avenue would involve investigating how political stakeholders could be effectively engaged in such a collaborative modeling methodology.

Working within planetary boundaries. While this approach may facilitate the collective construction of a "better" trajectory from a set of possibilities, it does not guarantee compliance with absolute planetary boundaries [46]. A key line of research would be to work on the notion of basic needs, with a democratic perspective to inform this kind of decision-making tool in a context where markets are further regulated (e.g. through quotas). Another important line of research would be to situate local design strategies in relation to global planetary limits.

7 Conclusion

In this paper, we build on the call to develop concrete systemic methods and tools in sustainable HCI [18] [32] [53]. We establish the importance of considering rebound effects when designing for sustainability [9] [14] [60], and the need for a methodology to enable designers and decision-makers to identify and understand existing and potential rebound effects in their magnitudes, formulate their own mitigation and design strategies, and be able to compare them over time. We argue that systemic design and systems dynamics are relevant sources of inspiration, and that collaborative modeling and simulation could be a promising opportunity to address rebound effects within a design process.

To assess the principle of a collaborative modeling methodology and explore its potential, we have developed a methodological prototype that includes the following steps: framing, preliminary investigation, identification of variables, initial diagram, consolidated diagram, prospective dynamic model(s), ideation, comparison of design strategies, and monitoring of effects. We have studied its possible contributions to a design process, and collected designers' perceptions during two workshops with ten professional designers.

During these workshops, systemic modeling was perceived as particularly relevant by most of the participants (9 out of 10), contributing to and integrating with design activities. We observed that the methodology enabled them to delve deeper into the situation, build a collective vision of the direct and indirect effects, generate ideas to mitigate the rebound effects, as well as to structure, enhance, and communicate these ideas. Modeling and simulation were perceived as highly promising for decision-making, allowing to combine multiple ideas, anticipate their impact, and compare alternatives. Most designers were convinced of the relevance of the quantitative aspect of the methodology (9 out of 10). Although some expressed that the quantitative consolidation of the diagram presented more challenges (4 out of 10), they believed that rapid skill development could be achieved through practice. The methodology was seen as aligning with a designer's skill set, provided they receive adequate training or support. It was also noted that successful implementation would require a multidisciplinary team.

Our findings allowed us to develop a proposal for integrating quantitative modeling into a design process. Finally, we discussed the limitations of the study, the contributions of the systemic modeling methodology, and open up new research directions, such as ideation tools for envisioning rebound effects, prospective data collection methods, involvement of policy makers, and evaluation of the strategies within the absolute planetary boundaries.

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