A new method to co-design agricultural systems at the territorial scale - Application to reduce herbicide pollution in Martinique

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1 Introduction

Since the Second World War, intensive agriculture has been responsible for negative externalities which affect the environment through excessive use of chemical inputs. Chronic environmental pollution is one of the most symptomatic examples of such negative externalities. To face this challenge, an agroecological transition of food systems is clearly required (Wittmayer et al., 2014). A shift towards agroecology requires three elements to be taken into consideration: (i) the characteristics of highly spatialized biophysical and ecological phenomena at a far bigger scale than that of the plot; (ii) the actions of all the actors who influence these phenomena, not only farmers but also other actors of the territory; and (iii) and interactions between farmers and the territory (Benoıt et al., 2012; Leenhardt et al., 2015; Veldkamp et al., 2001). From this point of view, increasing research considers territory as an object that needs to be designed in collaboration with the actors (Lardon et al., 2017). Concerning the design process, according to Prost et al. (2017), the complexity of territories makes it very difficult to establish *a priori* a precise definition of the object to be designed. However, a definition can be reached when a wide range of stakeholders take part in a collective design process that combines diverse forms of knowledge.

The design objectives in agricultural sciences have evolved in recent years in parallel with the growing role of territorial design (Prost et al., 2017). Accordingly, new design methods are also evolving, including the recent development of methods for the design of complex agricultural systems. These systems are made of : 1) the agroecological entities at different organisation levels (such as fields, farms, rivers, natural habitats, etc.), with the organized set of laws, rules and choices involved in their structure and functioning (Osty 1994); and 2) the actors involved in their management such as the farmers, and the other stakeholders of the territories and food systems (Doré et al., 2006).Examples of methods include serious games used for the design of a territorial project (Lardon et al., 2017); structured design approaches to design a sustainable agricultural sector and an agroecological park (Elzen and Bos, 2019; Romera et al., 2020); and innovative design approaches to design an agro-ecosystem (Berthet et al., 2016a). These methods are built on close dialogue between practitioners and scientists on the knowledge, know-how and solutions that already exist or which are needed to remove any obstacles from the paths of innovation, rather than the operational application of scientific discoveries (Meynard et al., 2012; Prost et al., 2017).

Because sustainable agricultural systems require a break with current production paradigms, and given its potential, innovative design merits further development at the territorial scale (Meynard et al., 2012). The C-K theory, developed in the industrial world to conceptually model participatory design reasoning, formalised the innovative design approach we used for this study (Hatchuel and Weil, 2003; Le Masson et al., 2011). The innovative design approach is iterative, allowing ongoing modification of the desired object, changes in the skills required, in the method of evaluation, the knowledge to be applied, and the mode of collaboration (Le Masson et al., 2014; Meynard et al., 2012). Recent studies have sought to adapt the innovative design approach to the agricultural plot (Berthet et al., 2016; Leclère et al., 2018; Ravier et al., 2018) and have made it possible to consider the territory as an object to be designed.

Innovative design methods lack the analysis of path dependencies and lock-in to innovation in a formal way. Nevertheless, both are required to identify the actors to involve as well as the cognitive biases that each actor will bring to the innovation process. Moreover, the evaluation of solutions in real situations is not generally carried out on objects as complex as a territory, while the process of designing innovations continues in their use. Berthet et al., (2016), after a comparative critical analysis of different design methods (including innovative design and serious gaming), recommend to use them in a combined way. Following their recommendation, we built a new method based on innovative design, combined with an analysis of the sociotechnical lock-in of the studied territory and with a serious game to get closer to the operational conditions experienced by the actors.

Our method was developed as part of a program to reduce the pollution of river water in Martinique caused by excessive use of agricultural herbicides. The method aims to identify radically new solutions at a scale at which it is very difficult to define objectives and performance criteria for each actor, since pollution of rivers by herbicides is subject to complex dynamics in space and time (Mottes et al, 2017). The paper is organised as follows: After describing the study site, we present the conceptual framework of the method and its implementation at the study site in four steps. We then present and discuss the results we obtained by applying the method and the scenarios.

2 Materials and Method

2.1 Study area

To create and test this method, we chose the Galion River watershed in Martinique (French West Indies) where the river is polluted by herbicides. This watershed covers 45 km², and the three main farming systems in Martinique are practiced there: sugar cane monocropping (*Saccharum officinarum*) (35% of agricultural land, 38 farms, 370 ha); banana monocropping (*Musa* spp.) (45% of agricultural land, 21 farms, 500 ha); and market gardening and food diversification (yam, tomatoes, salad, fruit, etc., 20% of agricultural land, 82 farms, 130 ha). Galion watershed includes a water quality monitoring system that has assessed the pesticide content of river water at weekly intervals since 2016 (Mottes et al., 2019). The major pollutants identified are chlordecone, herbicides and post-harvest banana fungicides; see Anckaert et Mottes (2019) (in French) for a complete list of the ~400 active ingredients assessed.

2.2 Conceptual framework of the method

Three methods were combined to build our method that meets new design needs in agronomy, i.e., a territorial scale approach that goes beyond the limited exploration of solutions. Our method combines a sociotechnical diagnosis (Fig1a) to identify the problem, use of the C-K method (Fig.1b) to open the path to possible innovations, and a serious game (Fig.1c) to refine and assess the innovations. With our method, the results are not known in advance (Fig. 1, d), it predicts the main properties of the object we want to design, in our case, a watershed with low concentrations of agricultural herbicides in the river.

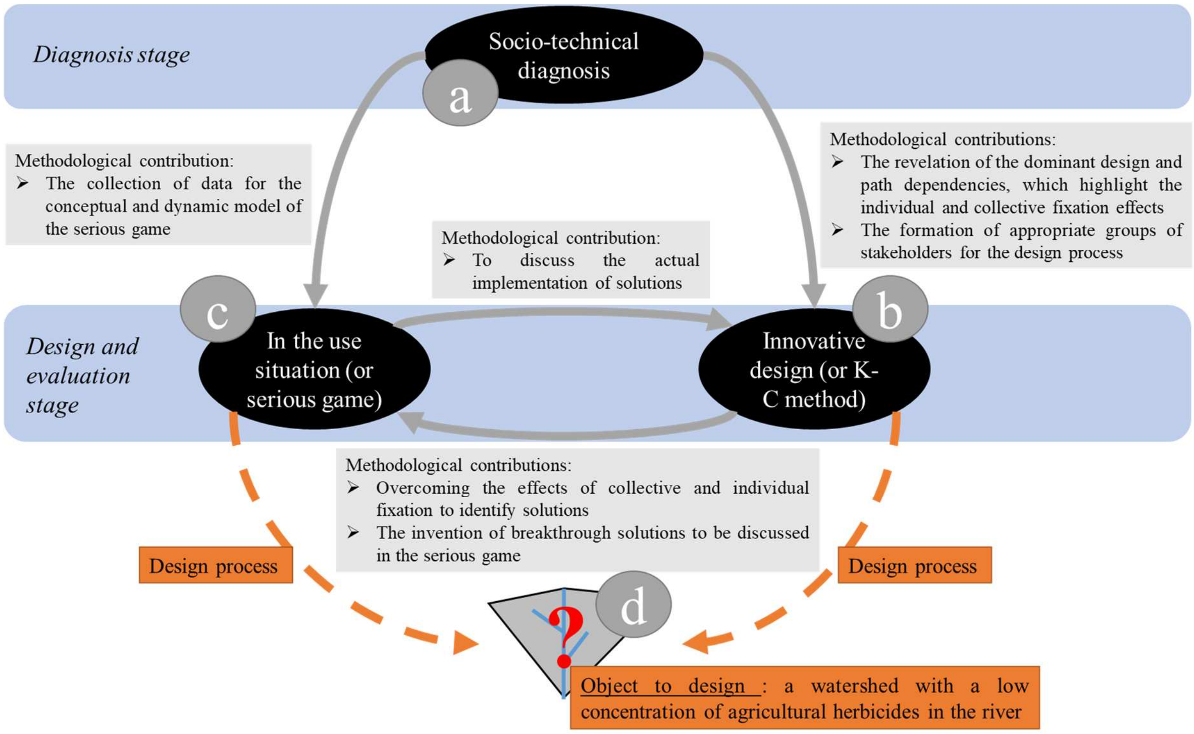

Figure 1: Conceptual diagram of our method which combines three methods. The grey boxes show the theoretical contribution of one method to another (a, b, c) (arrows). The whole method aims to design new watershed management (d).

2.2.1 Sociotechnical diagnosis

Agronomists maintain that a diagnosis is essential for the implementation of any design process (Doré et al., 1997; Meynard et al., 2001). A diagnosis makes it possible to: (1) build a shared vision of the concept before starting the process; (2) identify the actors to be associated with the process and the lock-in that characterises their innovation processes; and (3) choose how to start the creative process. To carry out the diagnosis (Fig. 1, a) an analysis of the socio-technical system supported by the multilevel analysis of Geels, (Geels, 2004), and an analysis of path dependencies (David, 1985) were performed. These approaches help distinguish the direct and indirect actors in the innovation process, the brakes and the levers, and the central design created by the path dependencies (Geels, 2004; Loorbach, 2007). Path dependencies may be associated with fixation effects, which innovative design seeks to depart from (Ezzat, 2017). Because our aim was avoiding a path that was already too deeply entrenched to allow for innovation, in our diagnosis, we used the tools of C-K theory to identify fixation effects. To this end, we produced a C-K diagram based on the results of the diagnosis of the socio-technical system (Della Rossa et al., 2020).

2.2.2 Innovative design

To meet the requirements of creating radically new innovations for territorial design, our framework included a period of collective creativity in which the actors were removed from the context of their usual practices. The driving force of our method is innovative design (Fig. 1, b), based on the theory of design called the C-K theory (Hatchuel and Weil, 2003; Le Masson et al., 2014). The C-K theory represents a design process as the interaction between and the co-evolution of two spaces, concepts, or ideas (C) and knowledge (K). A concept is an undecidable proposition, meaning it is neither true nor false, unlike knowledge of space K. When a concept of space C becomes decidable, it integrates space K and the design process is a success (Le Masson et al., 2014). For breakthrough innovations, it is necessary to enter original ideas in space C. This in turn requires modifying the definition of the object by adding unexpected characteristics to an initial concept (called C0), which instantiate the object to be designed (Agogué et al., 2014).

A standard C-K diagram is a conceptual representation of a design reasoning based on the C-K theory, in two spaces K (knowledge space) and C (concept space) (Fig. 2). In the C space, a *known concept* refers to a set of known and well characterised technical solutions that already exist, an *achievable concept* needs to be deepened to exist, and a *breakthrough concept* is far from the dominant design of the actors and usually does not yet exist (Agogué et al., 2014). These three types of concepts are summarised in a C-tree, structured horizontally from the least disruptive concept to the most disruptive concept with respect to the dominant design (Fig. 2). The C-tree partitions are inclusive, i.e. a sub-concept is included in its superior concept. A sub-concept highlights a characteristic of the superior concept. For example, if the superior concept is "a coffee cup", the sub-concepts may be the number of handles on the coffee cup. The concepts are linked to knowledge in the K space. The K space gathers knowledge which is more or less acquired and the knowledge that is lacking used to develop the concepts of the C space. The K space is organised as follows: *validated knowledge* is knowledge that is already acquired, often (but not only) knowledge of *known concepts*. *Knowledge in the course of acquisition* is the subject of dedicated research programmes, often (but not only) concerning *achievable concepts*. Finally, a *knowledge gap refers to* knowledge that is missing or not operable by the actors involved, often (but not only) concerning *breakthrough* c*oncepts* (Agogué et al., 2014).

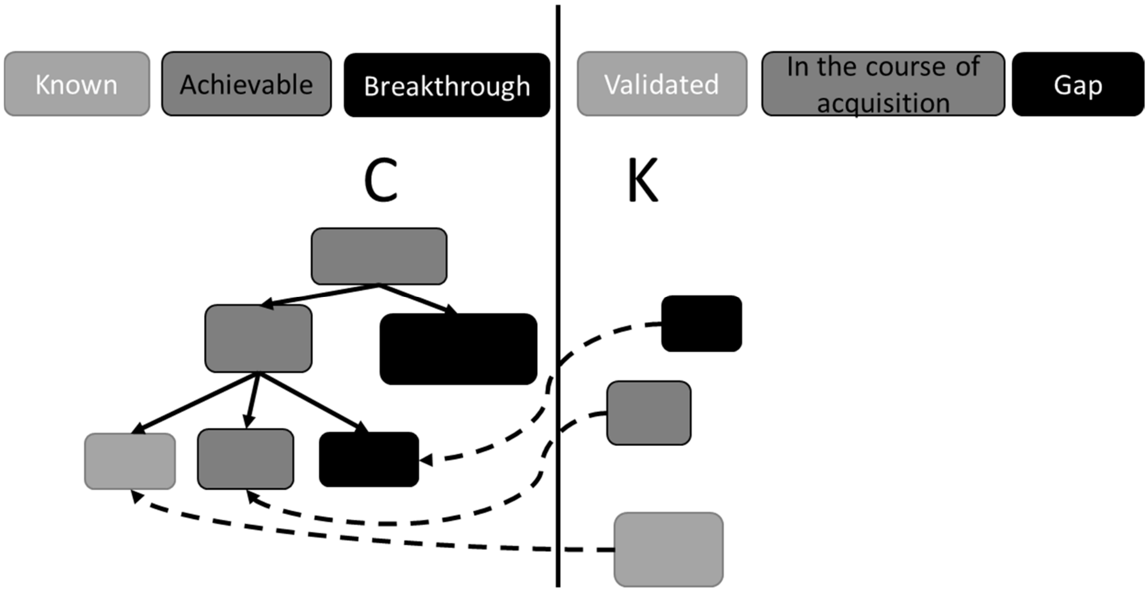

Figure 2: Simplified C-K diagram. In space C, we position known concepts (on the left, light grey), achievable (grey) or breakthrough (on the right, black), connected by dashed arrows with knowledge of space K: validated, in the course of acquisition, or identified as a knowledge gap (this colour code is used throughout the paper).

The innovative design theory was transformed into a method called KCP because of the order of the stages (Knowledge, Conception, Proposals) (Hatchuel et al., 2009) applied in agronomy (Berthet et al., 2016; Leclère et al., 2018; Ravier et al., 2018). Our study focuses on the stages of the method that make it possible to explore new ideas without fixation effects. According to Ezzat (2017), fixation effects are cognitive biases that prevent people from considering innovations that are radically different from what they already know. We discuss the stages of the KC method we selected from the KCP method (Knowledge and Conception) in the rest of the article.

2.2.3 In the use situation (serious game)

This method seeks to check whether the innovations designed by the actors "during workshops" fit the social and biotechnical systems of the territory under study and meet the end users' expectations (Fig. 1c). There are two reasons for checking. The first reason is that the innovation process continues after innovation is applied (Cerf et al., 2012). Observing changes in the object while it is "in use" is therefore crucial to assess whether it is operational. The second reason for checking how the breakthrough innovations fit is to assess their effects on the problem to be solved (in our case, herbicide pollution of a river). Both objectives are difficult to test in a territory in real life, because (i) the innovations are breakthroughs, consequently no references are available, (ii) pollution is the result of individual and collective actions on the common object, and (iii) the full-scale process can take a long time to complete. To at least partially, get around these difficulties, we filled the gaps via "design during use" (Fig. 1, c), (Cerf et al., 2012; Ravier et al., 2018). In other words, we simulated the use of innovations in the territory by means of a serious game which provides a secure space to test solutions (outside reality) and allows new knowledge to be created thanks to interactions between innovations and systems (Souchère et al., 2010). Our serious game was based on the WATPPASS computer model (Mottes et al., 2015) used to model pesticide flows to the river. This serious game allowed us to understand how the actors could collectively implement and adapt the innovations during their use (in this case, simulated use), and then to evaluate the reduction in the use of the herbicides and the potential reduction in pollution of the river that would result. The literature on the subject offers many examples of a game combining a set of rules, objects and roles that makes it possible to identify and analyse the personal and collective decisions of the actors, and to evaluate the effect of their actions (Moreau et al., 2019; Papazian et al., 2017; Sausse et al 2013).

2.3 Implementing the method in a territory

Table 1 summarises the procedure for implementing our new method in a territory. The four steps of the method are detailed in subsections §2.3.1 to §2.3.4. The research team was in charge of building the methods to help the actors build the innovations. Members of the research team were facilitators during the workshops.

Table 1: The four steps in the design process, in relation to the method, the designers (who actively participated in the construction of innovations), and the outputs of each step.

Steps	Method	Designers	Output
Step 1: Socio-technical diagnosis (Della Rossa et al., 2020)	Analysis of the connections between the socio-technical system and the watershed, using: - semi-structured interviews with the actors - review of grey literature on territorial development and agricultural development	Research team Actors: 23 farmers in the Galion watershed and 22 actors of the farming and territorial sectors (agricultural research center, technical institutes, producer groups, water managers, state organisations, territorial agricultural innovation service)	- Obstacles to and levers for innovations in weed management - List of actors to get involved in the design process - Path dependencies that constrain the creativity of actors
Step 2: Drawing a standard C-K diagram	Review of result of diagnosis using C-K theory tools	Research team	C-K diagram of the standard innovation pathways used by agricultural innovation actors in Martinique: - the fixation effects actors share - a breakthrough path to explore with the actors
Step 3: Innovative design innovation workshops (stage K and stage C)	A participatory workshop was held to share knowledge with all the stakeholders Three participatory workshops were held to explore new ideas in small groups	Research team Actors: farmers from the three agricultural sectors in the Galion watershed (banana, sugar cane, market gardening products and vegetables), agriculture and food	Phase K - identifying and highlighting knowledge gaps. Emerging concepts to explore original innovations in the next phase - design groups for the following step Phase C

		research centres, technical institutes, producer groups, pesticide distributors, a water manager, state organisations, a food company	- new pathways explored outside the usual innovation pathways - innovations that represent a break from the dominant design - new evaluation criteria for original innovations
Step 4: Serious game to continue design during use and to evaluate the reduction in pollution resulting from these innovations	A participatory workshop including a serious computer-assisted game	Research team Actors: farmers from the three agricultural sectors in the Galion watershed, technical institutes, producer groups, a water manager	- discussion of the feasibility of the proposedinnovations - development of original scenarios allowing varying reductions of the concentration of herbicides in Galion River

2.3.1. Step 1: Socio-technical Diagnosis

The socio-technical diagnosis conducted in Martinique consisted in interviews to identify actors linked to herbicide use and water quality (Della Rossa et al., 2020). The interviews were designed to identify: (1) the relations between actors within and outside their networks (business contracts, knowledge exchange, these actors' representations of the roles of other actors, etc.), (2) the effects of the interrelations on changes in weed management practices among farmers in the Galion watershed; and (3) the obstacles to and levers for technical innovation arising from rules governing Martinique's farming sector.

The grey literature was a source of agricultural information related to the three objects we were investigating: supply chains (Evaluation of Sustainable Banana Plan 1, Specifications of certification in supply chains such as GlobalGap, AOC rum, Organic Agriculture, supply chain contracts); farmers (technical documentation provided by the supply chain on agricultural systems in Martinique, thematic files on agriculture in Martinique for each sector); and territory (programmes and guidelines for agricultural development promoted by the State, European Development Programmes for the outermost regions of the European Union, water quality information, Galion River contract, urbanisation plans, Natural Parks Charter) (Della Rossa et al., 2020).

To identify obstacles to reducing the use of herbicides in agriculture in Martinique, we combined sociotechnical and territorial conceptual frameworks in a grid, which we then used to highlight the elements of the socio-technical system defined by Geels (2004), the rules, the actors, and the artifacts (Della Rossa et al., 2020). According to Geels (Geels, 2004), rules and regimes provide stability by guiding the perceptions and actions of the actors, which prevents them from proposing innovations that differ too much from these rules. What is more, these actors belong to organisations that are trapped in networks of interdependence that reduce possibilities for change. Finally, material artefacts imply relationships of complementarity and economic dependencies with other systems, and depreciation costs that further reduce possibilities for change, especially radical change (Cowan and Gunby, 1996). Identifying these different elements enables us to understand what drives innovation, as well as what prevents radical innovations from emerging in the existing socio-technical regimes. However, Geels limited his analysis to production systems, whereas our innovations concern a territorial system, itself composed of rules, actors, and artefacts in its three dimensions (material, organisational and conceptual (Laganier et al., 2002)) which may represent obstacles to radical innovation. This is why we added the identification of these elements to those of the socio-technical system usually considered in transition theories.

2.3.2. Step 2: Drawing the standard C-K diagram

A standard C-K diagram is a map of the state-of-the-art related to the object to be designed. It shows explored and unexplored innovation pathways, and the positions of existing innovation projects as well as those likely to emerge (Agogué et al., 2014; Hatchuel and Weil, 2003). It makes it possible to review conventional design pathways by proposing possible expansions (Agogué et al., 2014). This tool is used to increase the actors' innovation capacities.

For example, figure 3 presents a possible standard C-K diagram to design a coffee cup.

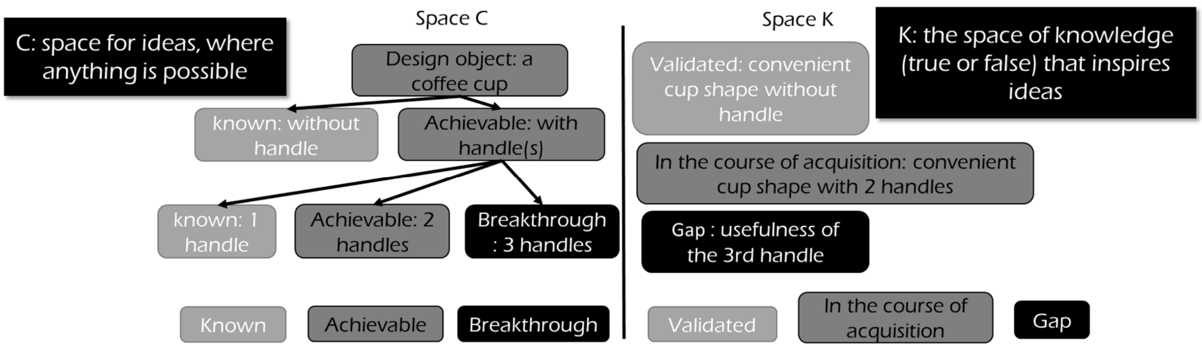

Figure 3: Example of a standard C-K diagram for the conception of a coffee cup. Space C contains known concepts (on the left, in light grey), achievable (grey) or breakthrough (on the right, black), and space K contains the knowledge that inspired the different versions, validated (in light grey), in the course of acquisition (grey) and knowledge gap (black)

In this example (Figure 3), we start the design by the number of handles the future coffee cup will have. In this case, the known concept is a bowl, i.e., a cup with no handle, based on knowledge of the shape of coffee cups with no handles (i.e. bowls) in shops. One possible achievable concept, meaning an existing idea but which requires further study, is a cup with one or more handles, a concept that we develop further depending on the number of handles. The next known concept is a cup with one handle, an achievable concept is a cup with two handles, and a breakthrough concept would be a cup with three handles, related to a gap of knowledge about the usefulness of this third handle in a funny way. With this simple example, the construction of a standard C-K diagram becomes clear: a dominant design for a coffee bowl with no handle, or for a cup with one handle, and the breakthrough, a coffee cup with three handles.

To start our real C-K diagram, we inserted the original concept (C0) we wanted to design: a watershed with a low concentration of agricultural herbicides in the river. Before drawing the C-K diagram, we have investigated the innovations currently under development, distinguishing between common, ignored and discarded properties, we analysed the history of the development of the innovations, the knowledge used to create the innovations, and finally we distinguished the degree of disruption of the innovations using the Hill and MacRae grid (Hill and MacRae, 1996). We identified which actor was involved in the development of each innovation, each actor's objectives and the formal and informal relationships between the actors, their agreements, and disagreements.

Following this method described below, the research team drew a standard C-K diagram by replacing the information collected in the diagnosis in Step 1. We then identified shared fixation effects with series of known concepts (Agogué et al., 2014). We used this information to encourage the facilitators of the design workshops, not to suggest innovations, but to steer the participants away from the pathways they are used to following.

Finally, we used this standard C-K diagram, particularly the most disruptive concepts, to start the creative design workshops described below.

2.3.3. Step 3: Innovative design workshops (stages K and C)

In this step, we alternated knowledge exchange sessions (Stage K) and groups of guided creativity (Stage C), based on studies that used the innovative design method (Ravier et al., 2018, Berthet et al. a&b, 2016; Le Masson et al., 2014). To the workshops, we invited the actors of the territorial and the agricultural sectors we had identified during the diagnosis stage who were likely to directly or indirectly influence the innovation process.

The aim of the K stage was to build a knowledge base which challenges received ideas and fixed definitions of objects, while creating common cognitive ground that is sufficiently rich to contribute to the creation of new concepts. Workshop K was designed to overcome the participants' fixation effects. At the beginning of the workshop, the research team presented the dominant design they had inferred from the diagnosis. This was followed by presentations by experts aimed at encouraging reflection among the participants beyond the effects of fixation. Although the dominant design was presented to theworkshop participants, it was not specifically discussed with them, because the focus of the workshops was on overcoming the fixation effects. In their presentations, the experts presented existing knowledge as well as existing problematic issues on the topic of processes of herbicide transfer and river pollution, design processes at territorial scale, and agricultural weed management in Martinique. The presentations made during workshop K are listed in table 2.

Table 2: Topics of the talks given by experts during the K workshop

Themes related to the object to be designed	Presentation
Transfer processes and the resulting herbicide pollution	Mechanisms of pesticide transfer at the watershed scale
The territory considered at the watershed scale	Shift towards more sustainable systems and the possibility for innovation combining production and value chains
Weed management by farmers	Response of soil macrofauna to the transition to organic farming

	innovative techniques for managing grass cover in the plot: cover crops and association with animals in orchards, plant cover in banana plantations, diversified agricultural techniques according to the type of crop

The experts' presentations were discussed with 26 participants (for a list of participants see "designers' column" in Table 1) and at the end of the K stage the research team was able to identify the new knowledge contributed by the experts and the other participants, and their collective's knowledge gaps.

The design step C is creative, and was facilitated by "projector concepts" based on analysis of the K stage. The aim of these concepts is to stimulate exploration of paths that depart from the dominant design. For example, as projector concept, we used "the agricultural sector of Galion watershed". This concept did not exist in the representations of the local stakeholders. Moreover, in Martinique, the main sectors are associated with only one crop and rarely include the territorial scale in their perception of development (Della Rossa et al. 2020). By associating the term "sector" with an environmental object "watershed", we encouraged the emergence of new forms of evaluating production in the watershed. Discussion took place in small groups and the composition of each group was decided based on the skills and knowledge of the participants that were relevant for the projector concept. The workshops were transcribed to capture any new ideas that arose from the discussions between participants. The research team then compared these ideas with the dominant design to establish the degree of disruption.

During these C-workshops, 15 participants (see Table 1) put forward their ideas related to the projector concept. To maximize the potential for creativity without fixation effects, the facilitator of the workshops was aware of the fixation effects, and redirected the discussion when it reached the previously identified (see 2.3.2). This guided the actors, including implicitly, towards different reasoning with the help of provocative examples and questions that deepened some of the concepts, or by emphasizing an original idea that came up during the think tank of these C-workshops, for example "what if the land did not belong to anyone?".

At the end of the K and C workshops, we were able to complete the standard C-K diagram and assess whether the K and C workshops had enabled us to deepen the breakthrough pathway. The process also informed us about the actors' expectations of the object under design and the additional criteria to evaluate it. An additional criterion is a criterion to evaluate the designed object that participants add during the design process. These new criteria completed the K space of the standard C-K diagram by helping define the object to be designed.

2.3.4. Step 4: Serious game to enable continuing design during virtual use and to evaluate pollution

For this design step, we were inspired by the tools used in the companion modeling method (Etienne, 2011). We first conceptually modeled the system under study using the ARDI method (Actors, Resources, Dynamics and Interactions) (Etienne et al., 2011) with data from the socio-technical system, and applied the conceptual model in a serious game, assisted by computer. The level of pollution was calculated from a validated pollutant transfer model validated and with data presented in (Mottes et al., 2015, Mottes 2013, Bizien, M. 2018).

The model of the WATPPASS-Game is based on two modules, an agronomic module and a pesticide transfer module.

The agronomic module simulates the development and growth of the crop and weeds in an integrated and qualitative manner (4 different stages defined by height and leaf area index) as well as competition for light in the plot using the Beer Lambert law (Mottes 2013). The time step of this module is three months, which was selected as a good compromise between precision and operationality in the design of the scenario at the watershed scale. Location, season, competition for light, and agricultural practices are the factors that influence the growth of crops, weeds, or both. Players update their decision concerning the practices every three months.

The pesticide transfer model uses a metamodeling approach (3 480 000 total runs) to assess the amount of herbicides exported from the plot through runoff and leaching for a period of 30 years after each pesticide application. To do so, 5 800 application conditions on the watershed (soil, place, type of crop, crop stage, weed cover, application equipment, position of application, etc.) were simulated 600 times each at a random time step to obtain average emission curves for runoff and leaching (Bizien 2018) in the different situations. Each time a herbicide is applied in the watershed, depending on the location of application, the season and the type of soil (sensitive factors according to Bizien (2018)), the module selects the appropriate 30-year emission curve and sends it to the watershed system which routes it to the outlet. Routing depends on the distance between the plot and the river system in the watershed according to the formalism described by Mottes et al. 2015 adapted to the situation of the Galion watershed. The quantity of pollution at the outlet are then broken down into a weekly time step. The principle of the game was as follows (Fig. 4): the farmer-players (Fig. 4, a) had to control the weeds growing on their own farm, which is located in the watershed (Fig. 4, b), and to choose innovations (designed during the KC workshops) to implement, given the financial and labour resources available to them. A territorial manager-player (Fig. 4, c) had additional resources to support the implementation of these innovations, or not. The agricultural sectors were representative of those of the players who participated in the KC workshops and among the farmer-players who took part in the serious game (see Table 1). The game was assisted by a computer model inspired by (Mottes et al.,

2015) and (Mottes 2013) to connect weed management practices and river pollution. The computer-assisted game (Fig. 4, d) made it possible to assess the effects of players' actions on crop and weed dynamics, and on herbicide pollution of the river in real time. The land use in the game is representative of the real land use in the Galion watershed. All we did was to group several farms of the same type to use 8 players instead of 141 farmers.

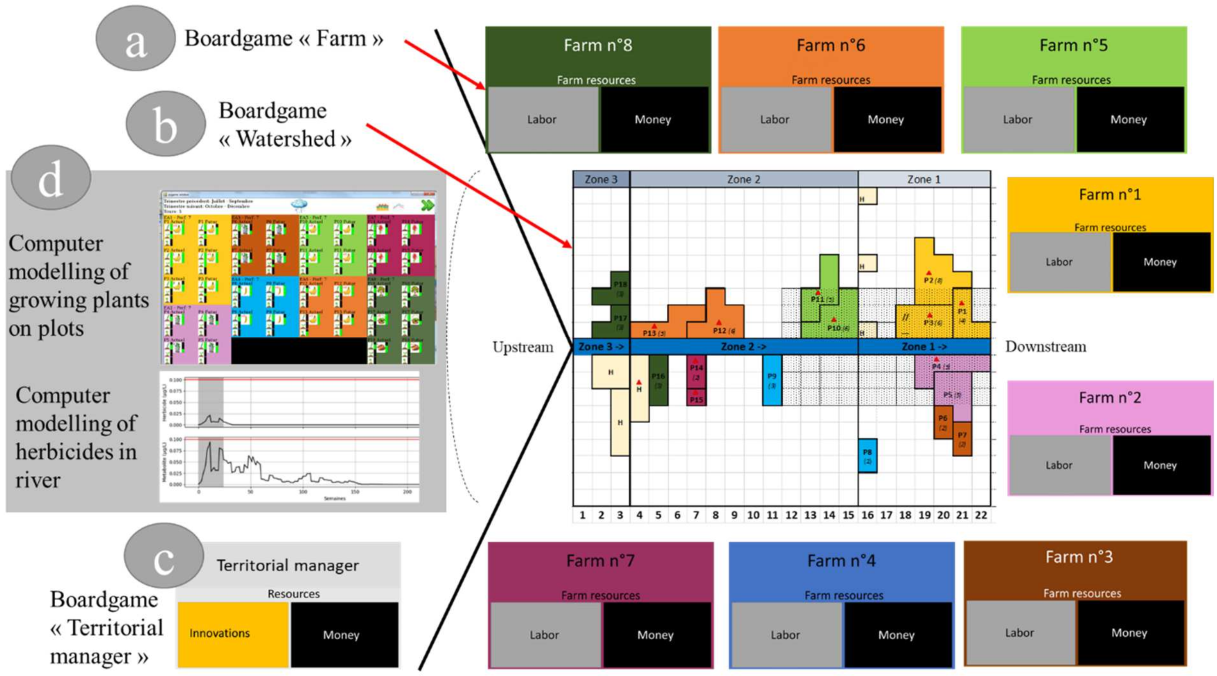

Figure 4: Diagram of the organisation of the serious game. Farmer-players have resources on their farm (a). The plots are located in the study watershed (b). A territorial manager-player (c) discusses the conditions for implementing the innovations with the farmer-players. The players make their decisions based on the growth stage of the plants and weeds in their plots, and on the level of herbicide pollution of the river computed in real time (calculator inspired by Mottes et al. (2015) (d))

At the beginning of the game, we let the farmer-players play with no advice and no innovation, river pollution is set at zero to establish the starting situation of pollution. When an herbicide pollution peak in the river was announced, all the players started discussing implementing innovations to solve the problem.

The entire workshop was filmed, and the games including the players' moves were entirely recorded. It was therefore possible to study both the individual and collective behaviour of the players, changes in their farming resources over the course of the game, as well as to replay certain actions with the model to isolate the impact of an action or set of actions on the level of pollution of the river. We then analysed the data concerning the individual and collective actions of the players, and distinguished three scenarios of agricultural organisation of the watershed. The scenarios correspond to different associations of collective innovations chosen by the players who formed groups with a specific function and produced specific results with respect to river pollution. We then analysed these scenarios from the point of view of water pollution and using the new evaluation criteria identified in the K and C stages.

In the game, we chose not to provide information on the respective responsibilities of the farms in river pollution, so as not to turn the game into the usual dead-end debate. We assumed that without any assistance with interpretation, the actors would become more aware of their representation of the responsibility of banana farming, thus breaking the collective dynamic. Our hypothesis is consistent with the statements of Kellon and Arvai (2011), where preferred alternatives pre-exist among the actors of a decision-making process concerning natural resources, and the facilitators are responsible for building informed and defensible alternatives with the actors.

Finally, we analysed the results of the method with respect to the relevance of the combination of the three theoretical and methodological frameworks for our design objectives: changes in the territorial object; breaking away from the dominant design, the innovations imagined by the actors; and the potential implementation of these innovations in real life.

3. Results

3.1. From the identification of path dependencies to the standard C-K diagram, the starting point for design

The diagnosis showed that all the agricultural sectors (sugar cane, banana, and diversification crops) have specific path dependencies but share the one that considers innovations only at the scale of the plot (Della Rossa et al., 2020).

The production objectives are specific to each sector. The banana sector wants to move towards an agroecological system that preserves the monocultural system. As a result, it selects weed management innovations aligned with that choice (such as associating banana with non-marketable cover crops). The sugar cane sector also wants to continue its monocultural system, and stay close to the sugar factories, in addition to not challenging mechanised harvesting. This attitude reduces the possibilities for innovations in weed management by almost only searching for (1) mechanical solutions that are consistent with mechanised harvest, or (2) varietal improvement. The agricultural diversification sector wants to move towards strong agroecology, with significant degrees of diversification at the plot and farm scale (with weed control practices that are mainly manual or that involve crop combinations, or even crop / livestock combinations).

We also found that the agricultural sectors are structured independently of each other, and almost never interact (Deffontaines et al., 2020; Della Rossa et al., 2020). They also have preconceived ideas about other sectors, in particular farmers in the sugarcane and diversified agriculture sectors, who think herbicide pollution in river is mainly the fault of the banana sector. In fact, each agricultural sector have its own Research & Development and supply chain actors, but different degrees of financial and material resources. The motivation of all three agricultural sectors in reducing their use of herbicides is not connected with a desire to reduce river pollution, or to foresee future regulations (banana and sugar cane growers), or to reduce the health risk for farmers (diversification). Technical assistance is available to banana farmers thanks to the strong vertical structure of the sector around a central actor that conducts active agricultural research and provides advice. Less assistance is available for sugar cane, especially for small-scale farmers, as the central actor has limited capacity to structure the sector and no funds for innovative research and advisory services. Finally, the diversified farming system sector has few financial and material resources, with 20% of the farmers divided between six producer organisations. Research and development, mainly represented by the chamber of agriculture, has difficulty in identifying innovations to respond to the wide range of existing situations.

Agricultural and territorial development programmes remain based on the objectives and drivers of innovation defined within each agricultural sector, because public authorities delegate the task of deciding on the guidelines and rules for funding these programmes to the main stakeholders of each sector. Thus, the scale of the watershed does not exist in agricultural innovation processes, particularly weed management. This implies that the issue of "water quality" (here of the Galion River) receives scant attention in the sector's innovation approaches. The agricultural sectors in Martinique have two strong path dependencies that influence their dominant design: (i) they innovate within their own agricultural sector; and (ii) they innovate mainly at the plot scale, with very little consideration for the territorial scale.

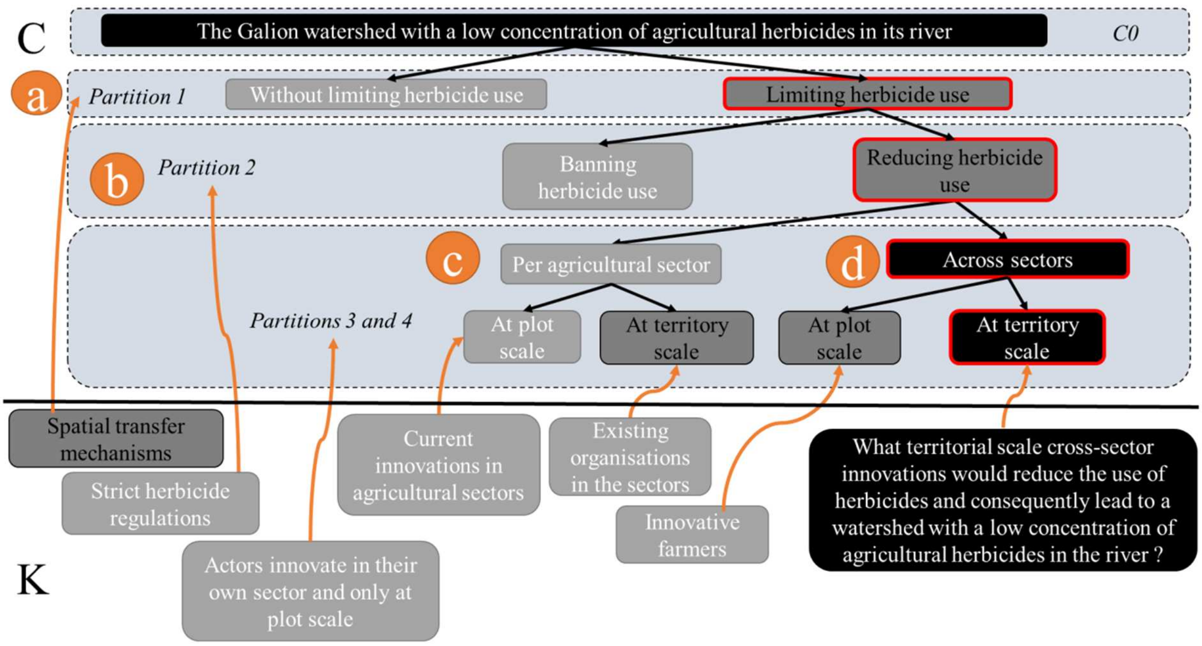

Figure 5: Standard C-K diagram resulting from the socio-technical diagnosis. The boxes use the same colour code as that defined in Fig. 2: known concepts (light grey), achievable (grey) or breakthrough

(black). Arrows identify knowledge related to its corresponding concept. The boxes outlined in red in the C space represent a departure from the path of innovation from the collective fixation effects of actors of innovation in weed management in Martinique. The letters "a", "b", "c", "d" locate the elements of the figure described in the text.

Based on the previous socio-technical diagnosis, the research team built the standard C-K diagram shown in Fig5. The partitions a and b represent the context of rules in which the actors evolve, while partitions c and d are the rules produced by the actors concerned in Martinique. First, knowledge of pesticide transfer mechanisms distinguished two concepts in partition 1 (Fig. 5, a). The first was to reduce pollution without reducing herbicide use. Some actors, who assumed the molecules could degrade before reaching the river, wanted to limit the concentration of herbicides in the river mainly by creating physical barriers to slow down the flow to the river. However, most of the actors of agricultural innovation in Martinique, as well as the territorial authorities, supported the second concept in partition 1, i.e. reducing the use of pesticides by individual farmers. Partition 2 (Fig. 5, b) concerns changes in European regulations that ban the use of an increasing numbers of herbicide molecules, whereas most of the actors of agricultural innovation only wish to reduce their use. Partitions 3 and 4 (Fig. 5, c and d) concern the two collective fixation effects of the actors of innovation: innovation within their own agricultural sector, mainly technical innovations at plot scale. This is why in partition 3, we separate the fixation effect in the concept of innovating in each agricultural sector from the breakthrough concept of innovating in a cross-sector way, and in partition 4, we separate the fixation effect in the concept of innovating at plot scale from the breakthrough concept of innovating at territorial scale. The usual trend favours the left-hand concept (Fig. 5c). When this dominant design was presented to the stakeholders in workshop K, despite requests for questions and comments, no participant expressed either agreement with or opposition to our conclusions.

The building of the standard C-K diagram made it possible for the research team to see a path emerging (on the right in Fig. 5d), where the actors could innovate in across sectors at territorial scale. This conceptual path represents a dramatic shift from the fixation effects of the actors of innovation in weed management in Martinique. Some innovative farmers belonging to different agricultural sectors who exchanged technical knowledge were already innovating in this way. Nevertheless, until now there had been no innovations at the scale of the territory, across sectors, that would have reduced herbicide use and consequently herbicide pollution of the river (Fig. 5, d). We therefore continued along this path with the actors, in innovative co-design workshops, to try to fill the corresponding knowledge gap: **What territorial scale cross-sector innovations would reduce the use of herbicides and consequently lead to a watershed with a low concentration of agricultural herbicides in the river?**

3.2. Fifteen innovative proposals emerged from the creative process

At the end of the K and C workshops (step 3 of the method – see above), the actors imagined 15 innovations starting from two new partitions of the C-K standard diagram. Fig 5 presents the C-K diagram constructed from the characteristics and knowledge of these 15 innovations. Fig 6 is a continuation of Fig. 5 (for the sake of readability, only the additional partitions and new knowledge are included in Fig. 6)

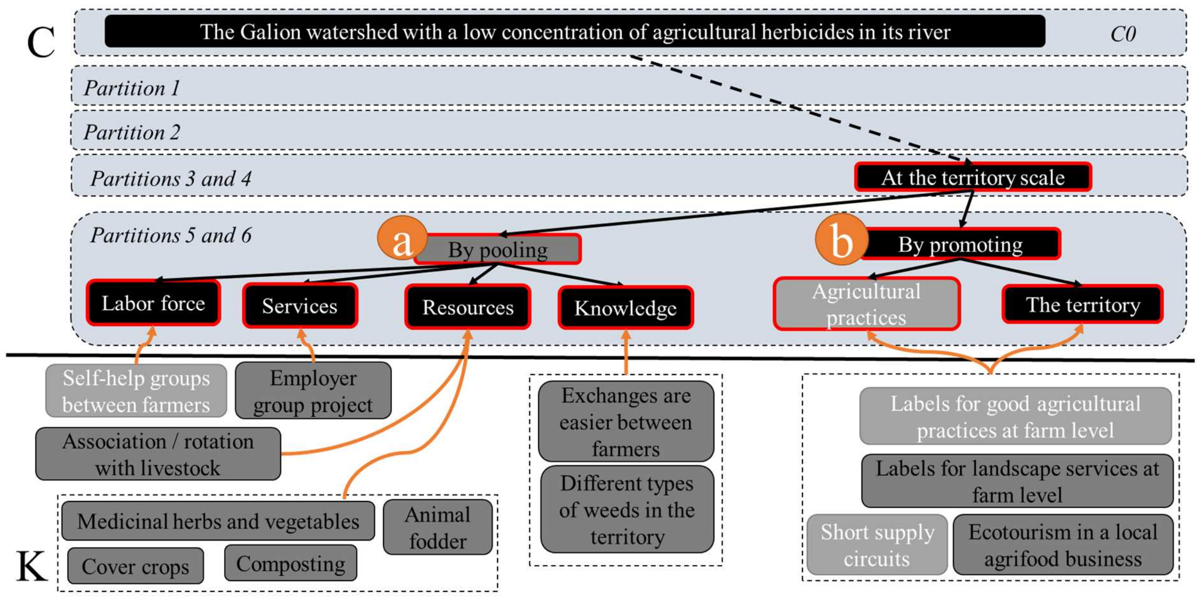

Figure 6: Standard C-K diagram at the end of workshops. The boxes use the colour code defined in Fig. 2. known concepts (light grey), achievable (grey) or breakthrough (black). To facilitate readability, partitions 1 to 4 are not complete here (dotted arrow), and the K space only sums up the knowledge that emerged during the workshops. Two new partitions (5 and 6) appeared in space C at the end of the workshops. The concepts framed in red are all part of the innovation pathway that is breaking the collective fixation effects in weed management in Martinique.

Space C in Fig 6 only presents the characteristics of the innovations, not the innovations themselves, and space K in Fig 6 only presents the knowledge that was used to build the innovations, not the innovations themselves (see section 2.3.2). The innovations are listed in Table 2. The innovations cited here by the actors are innovative because they are not found on the territory of Martinique, or more particularly, in the Galion watershed territory, because our actors' innovations were designed with the main objective of reducing the use of herbicides, and because they are considered at the watershed scale independently of the agricultural sector to which they belong.

Table 2 lists the 15 innovations created during those workshops.

Line	Innovation	Description of innovation	By pooling	By promoting
1	Community of practice	Creation of a discussion group between farmers, all agricultural sectors included	knowledge	
2	Catalogue of judicious associations with "weeds”	Creation of a catalogue to identify and select local plants adapted to each type of crop for use as a competitive cover crop for weed control	knowledge	
3	Brush cutting service provider	Creation of a partnership between farmers who are located geographically close to each other in the watershed and a brush cutting company	services	
4	Market for « weeds »	Creation of a market of weeds for human consumption (medicinal plants, vegetables) or for use as animal fodder	resources	
5	Collective composting	Creation of an association of farmers for the management of one or more composters, for "weeds" produced by farmers and municipalities	resources	
6	Mutualization of the services of an itinerant livestock breeder	Creation of an association of farmers or a partnership that employs a livestock breeder with his herd to graze weeds growing on farms located geographically close together in the watershed	services	
7	Koudmen	Creation of a mutual aid group between farmers from different sectors in the watershed for weed control on each other’s farms	Work force	
8	Co-exploitation of plots	Creation of partnerships between farmers from different agricultural sectors for the development and maintenance of fallow land or of land between main crops	resources	
9	Galion store	Creation of a local distribution network for products produced by the farmers in the watershed, in a store and/or under contract with consumers		Agricultural practices Territory
10	Diversification to orchards under contract	Creation of a partnership contract between farmers in the watershed and the processing plant in the watershed, to increase financial resources for better agricultural practices		territory
11	Showcase Watershed	Agreement between farmers in the watershed to formalize and adhere to a charter of good practices		Agricultural practices Territory
12	Grant for landscape conservation	Creation of a grant to conserve landscapes in the Galion watershed, (definition and collective description of these landscapes by the stakeholders of the watershed)		territory
13	Tourism	Creation of a network of tourist farms in different agricultural sectors associated with other tourist activities in the territory		territory
14	Training modules according to the context	Creation of training based not on crops but on the different soil and climate contexts, and possible innovations with no herbicide use	knowledge	
15	Consumer training centre	Creation of a training centre for consumers, focused on agriculture and issues of pesticides residues in water in products and alternatives	knowledge	

The breakthrough path was pursued in more depth: (i) based on the characteristics of the watershed; (ii) in comparison with examples of innovations underway elsewhere; and (iii) in comparison with existing examples in the territory in certain sectors or on some innovative farms. Without detailing all 15 innovations, here we present their guiding principles.

Regarding pooling (Fig. 6, a), the actors had several ideas concerning pooling the work force, for instance, by creating a work group composed of farmers living in the territory to help with hand weeding, pooling the services of a low-cost brush-cutting provider or of an itinerant cattle breeder to graze weeds on neighbouring farms. By extending the functions of weeds, the actors also thought about pooling grass resources for sale (for medicinal purposes, as vegetables, as animal fodder), or using weed resources and composters to make shared compost or to feed animals on neighbouring farms. The two last innovations are only compatible with hand weeding. Because the farmers appreciated exchanging knowledge with other farmers, and because weed control is an integral part of all cropping systems, they also wanted to continue pooling their knowledge despite belonging to different agricultural sectors. This innovation could help them better understand the dynamics of the territory's weeds, and to find and share solutions for weed control without the use of herbicides.

Regarding promotion (Fig. 6, b), the actors wanted to promote the Galion watershed based on its agricultural identity, first through sustainable practices such as reduced herbicide use, then by developing a label for their crops (either specific to the basin, or part of an already existing quality label), or by creating short supply circuits specific to the watershed. Another idea for promoting the watershed was based on the creation of an ecotourism circuit label based on the rich agricultural diversity of the watershed, which is representative of agriculture in Martinique. This label would provide financial resources that could then be used to reduce herbicide use. The innovations were not only designed during the workshops, for instance, the idea of selling certified products from the watershed was put forward on the ecotourist circuit.

Group discussions also made it possible to identify the criteria (see 2.3.3) the stakeholders preferred to evaluate a watershed with low concentrations of agricultural herbicides in the river that was the object of the design, namely: (i) reduced herbicide use; (ii) increased financial resources for farms (mentioned by non-farming stakeholders); (iii) reduced work time for farmers (mentioned by the farmers); (iv) promotion of the watershed as a place of good agricultural practices; and (v) more pooling of resources between farmers to create solidarity.

To sum up, at this point we had successfully explored the breakthrough path, but the best way to implement the innovations to reduce the presence of herbicides in the river remained to be found. This was this knowledge gap we wanted to fill with design in use, using the serious game.

3.3. Game to simulate the design of innovations in use

The research team selected six innovations out of the 15 (Ecotourism; a charter “Watershed with good agricultural practices”; Farm diversification to arboriculture; Itinerant livestock breeder; Brush cutting service provider; Mutual aid group between farmers) to cover the entire C tree of the diagram C-K in Fig. 6, i.e. by selecting an innovation by each concept of partition 6, and to cover all the evaluation criteria. These innovations were implemented in the game.

During the game, players chose which innovations they wanted to apply. Groups of players were formed based on a shared choice to stick to certain collective innovations. This enabled us to distinguish three scenarios, which we evaluated with respect to herbicide pollution in the river and additional criteria (Table 3). All three scenarios led to a in reduction in herbicide pollution of the river.

Table 3: Innovation tested in the three scenarios run during the serious game workshop

	Scenario 1	Scenario 2	Scenario 3
Innovations chosen by the players	Ecotourism Brush-cutting service provider Diversification to orchards under contract	Charter « Watershed with good agricultural practices » Brush-cutting service provider Itinerant livestock breeder	Charter « Watershed with good agricultural practices » Farmers' mutual aid group Itinerant livestock breeder Universal grants

Scenario 2 is the one that fulfilled the most criteria, especially in increasing the labour force available for agricultural tasks on 75% of the farms. Financial resources remained stable for 75% of the farms and were reduced for 25% of the farms. This led to a 76% reduction in herbicide pollution of the river. During the game, new relationships were formed between the actors. First, implementing the innovations brought together actors who in real life are not so close. Second, relationships were also formed between players, especially between the water manager and the farmers. Concerning the relationships linked to the implementation of innovations, the scenarios put farmers in the same sector in the watershed in touch with one another by getting them to participate in the same charter, or in the ecotourism circuit. Finally, these new farmers' networks were put in contact with other actors of the territory, in particular those involved in water quality monitoring, which enabled certain collective innovations to be implemented through subsidies, or in collaboration with service providers outside the watershed. As a result, by combining the combinations of successful innovations within the territory, that have been played in the three scenarios, we were able to design watershed-scale and transboundary solutions to achieve low concentrations of agricultural herbicides in the river (Fig. 7). It was the combination of the solutions within the watershed territory in the game that led to the successful design of a new configuration in this watershed, and to low concentrations of agricultural herbicides in its river. This new watershed represented the initial C0 concept we had wanted to design all along.

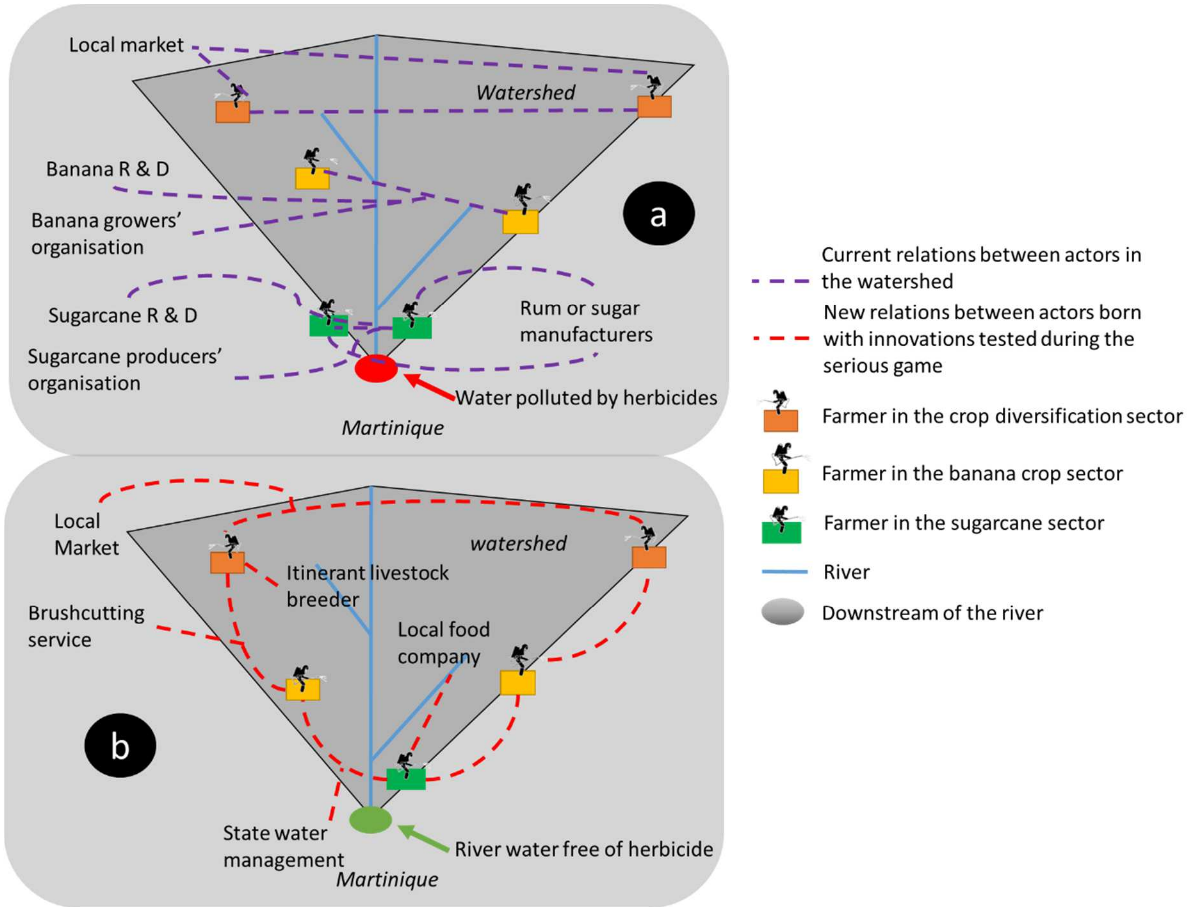

Figure 7: Schematic diagram of the main relationships that existed in the watershed before the design process began [purple dashed lines in (a)] and at the end of the design process [red dashed lines in (b)]. The new relationships [red dashed lines in (b)] between the actors in the watershed were created during the serious game. Farmers from the three agricultural sectors became acquainted when the innovations were tested. Members of these new farmers' networks also met other actors already present in the watershed, as well as new actors outside the watershed. These new relationships help reduce the level of herbicides in the river [green oval].

4. Discussion

4.1. Advantages and limits of the method

Our method enabled us to propose a new way to organise the watershed and to reduce herbicide pollution in the river, as well as the emergence of new networks between actors at the watershed scale and across agricultural sectors and different types of actors. We therefore recommend its use in other territories which require changes in collective practice, particularly, but not only to limit pesticide pollution. In this section we explain how this new method enabled this success, along with its limitations, and present a reformulation of the method for generic use.

Adapting theoretical and methodological frameworks to the territory

As recommended by Belmin et al. (2017) and Raven et al. (2012), in our socio-technical diagnosis it was necessary to spatialize the concept so that it could be applied to the small territory represented by the Galion watershed. Indeed, the framework of a sociotechnical system is appropriate to study the normative and regulatory rules that apply to a territory, and to focus on institutional mechanisms (Lamine et al., 2019). In our case, the watershed is not a defined space for agricultural management, nor a space that is present in the representations of most of the actors, except for actors of water management. We therefore had to study these rules at the scale of the whole island of Martinique, and then to make assumptions about their impact within the spatial limits of the watershed. Other authors who sought to link the socio-technical system to a territory encountered the same difficulties. By carrying out a more local resizing, these studies established the boundaries of the system to be studied through territorial or sector projects related to the existence of normative and regulatory rules (e.g. PGI clementines in Corsica (Belmin et al., 2017); the organic agriculture sector (Lamine, 2012); or institutional projects (Allais and Gobert, 2019)).

Choices made by the research team that guided the design process

In the creative exploration stage (stage C), we made choices concerning the fixation effects to be overcome in the process that would increase the emergence of innovations on a territorial scale. That is why we focused on two fixation effects, i.e. (i) innovating within their agricultural sector and (ii) at the plot scale, that were common to all three agricultural sectors, and ignored the fixation effect related to sugar cane and banana monocropping. Although the innovations designed also concern the banana and sugarcane sectors, they do not directly call into question the successions of monocrops (banana, sugarcane). This fixation effect, although clearly identified in the diagnosis, was not retained in the following stages because it did not concern all the actors, in particular the diversified agricultural sector. This phenomenon was also reported in Ravier et al. (2018), where the innovations developed did not include the scale of the innovations, and in Vourc'h et al. (2018) who sought to develop transdisciplinary projects, but where all the new projects still focused on technical changes on farms. This phenomenon underlines the importance of the choice of fixation effects to be overcome, which guides creative exploration. To overcome the fixation effect on monocropping, the KC workshops should have focused on overcoming this particular fixation effect. As a result, certain paths were not explored, even when they could have led to breakthrough innovations.

Building consensus

In C-K theory, changes in the participants' knowledge lead to changes in the definition of a concept, and in turn, in the representation of the object. During the workshops, we observed changes in the representations of the object to be designed – which made it possible to collect new evaluation criteria from the actors – and a desire to create a specific agricultural identity for this watershed. This is consistent with the findings of Bretagnolle et al. (2018) and Prost et al. (2003), who reported that knowledge is more a construction than a discovery. Allowing the ongoing review of the fundamental properties of the object under design between the actors is a major advantage in innovative design (Berthet et al., 2019). What is more, we went from design that considers the territory as a context, to considering the territory as a design object, which is part of the changes in the relationship between design and territory as understood by Parente and Sedini, (2017). The actors changed their representation of the watershed, which they had initially not perceived as a management scale. In fact, participatory design processes like ours, focused on the development of a new social and ecological system, reinforce the actors' sense of ownership and responsibility (Berthet et al., 2019).

Actors' motivation

During our study, we succeed in achieving the necessary representativeness of the actors, but we had problems keeping the same actors involved throughout the process and witnessed a decline in participation over time.

We chose to set up a collaborative participation process steered by the researchers, with the active collaboration of the participants and sharing of knowledge about the watershed. However, the development of the design method was not discussed with the actors, and we partially failed to clearly explain our objectives regarding the methodological development of the design process. According to Kellon and Arvai (2011) this is something that is regularly criticized in participatory processes. But sharing our design objectives with the actors is difficult in a method where the object to be designed is not defined right at the start but is constructed progressively. Barreteau et al. (2006) argue that when participants do not really know what to expect in a participatory process, or even when certain power relationships between actors are at stake (Barnaud et al 2010), there may be disappointment, which may jeopardize their participation. To overcome this problem, Pahl-Wostl et al. (2007) point to the need to develop a sense of legitimacy in decision-making among all participants, as this encourages them to participate in the process. Kellon and Arvai (2011) and Mintrom and Luetjens (2016) argue that this requires that the collective of actors do not feel they are being used by the researchers, i.e. perceive their participation as a mere formality, but feel they really participate in decision-making. To avoid this problem, it should be made clear to the participants at the start that the object to be built has not yet been defined, and that the aim of our participatory method is to develop the collective creativity of the participants, and in this way to incorporate their decisions into the design of the object.

The power of the KC method to motivate participants can be examined in terms of the originality and novelty of the solutions designed with the method. In some workshops, participants said that they disliked using projector concepts (see section 2.3.3) that were too far removed from their own representations. Others questioned the feasibility of very original solutions. It is thus necessary to examine the difficulties peculiar to the KC method, i.e. maintaining the involvement of a group of actors throughout the design process, and how this difficulty can be overcome. As innovative design was originally developed in companies (Hatchuel, 2018) where participants are generally encouraged to work together and who share the same corporate objectives, the capacity of the method to motivate actors has not been challenged to date. However, the difficulty in getting actors involved in processes outside companies has been reported in other studies (e.g. Pluchinotta et al., 2019). In these studies, the facilitators used different strategies to keep the actors motivated throughout the process, for instance, by linking stages K and C on the same day (Berthet, 2013; Ravier et al., 2018), or using semi-structured interviews with the actors in stage K rather than collective workshops (Pluchinotta et al., 2019).

About the future of this participatory process

This participatory process responds to the changing relationship between design and territories, by designing for territories. This approach automatically involves stakeholder participation and the creation of intermediate artifacts (such as the game or the standard C-K diagram) to compensate for the excessive complexity of the system to be co-designed (Parente and Sedini, 2017). As the territory is a non-static, constantly changing context, design tools and devices must be flexible (Parente and Sedini, 2017), which in turn, implies that this type of device should take the form of evolving and perennial institutions. With financial support, this participatory process could become permanent by becoming an entity inspired by the socio-ecological research platforms presented in Berthet et al. (2019) and Bretagnolle et al. (2018). Those platforms will enable the capitalization of knowledge on the dynamics of the socio-ecological system, while developing collaboration and synergies between design facilitators, ecologists, and local actors Berthet et al. (2019). These platforms are not limited by traditional disciplinary boundaries, since they operate at a spatial scale that is large enough to involve all actors, and use systems approaches to study the links between ecological and social systems (Bretagnolle et al., 2018). These platforms can coordinate the actions of stakeholders by taking the knowledge of all the niches of the sociotechnical system into account, thereby safeguarding the niches through their co-evolution due to the fact that the stakeholders no longer compete with each other (Le Masson et al., 2012). That was the case here, where all the stakeholders of the agricultural sectors that innovate in weed management were brought together to design scenarios combining and hybridizing different technical innovations. But our work remains theoretical, and it would be necessary to continue the development of the C0 by implementing some combinations of innovations in the watershed.

To this end, a strategic vision of the future development of the territory needs to be designed using these platforms, i.e. a preliminary framework of values and means between the actors, in order to help the actors identify what they consider the best way to act (Parente and Sedini, 2017). As Mathevet et al. (2016) argue, with the aim of preserving natural resources, these strategic visions can take the form of ecological solidarity with a symbolic agreement between actors, on a territorial project.

4.2. Towards a generic method

The structure of our method (Table. 1), which combines four steps to design new ways of organising territorial food systems, was successfully tested in this study. Here we complete it with four possible improvements.

During the diagnosis (step 1) or at the beginning of the process design (step 2), our experience shows that the initial questions that can arise - particularly in a group of actors - need to be discussed with all the actors to achieve satisfactory reformulation and clarification of their expectations of the participatory process. This will allow the actors to assess the time they can allocate to the process, but also allow the facilitator to adapt his or her participatory process to the possible need to motivate the group.

We recognise the efficiency of using the KC method in overcoming the fixation effects of actors during Step 3 (the creative step). The K stage should open the actors' minds to breakthrough ideas by sharing current knowledge, lack of knowledge, and original examples. Facilitators need to be aware of all original knowledge or examples that could feed this dynamic process. In the C stage, the facilitators need to be aware that projected concepts may disturb the participants, and that the actors will have a strong reflex to return to their fixation effects. This is why facilitators need to be trained in innovative design and be ready to give examples from other innovative design case studies to reassure the stakeholders about the advantages and seriousness of these destabilizing conceptual detours, and of their potential for generating new ideas. We had difficulty with one C workshop based on the concept of the " Galion Watershed Grassland Management University", especially with the word "university" which was a problem for the participants, as it seemed absurd and out of place. We were unable to reassure the participants, and this workshop was in fact the least productive of the three C workshops. At the end of this stage, the facilitators should be able to add evaluation criteria to the object designed, based on the actors' own new ideas.

We also recognise the effectiveness of using a serious game, with or without a computer simulation model (step 4) to develop the properties of situated innovations (even simulated ones) to continue to design innovations. We suggest that the conceptual representation of the system concerned, as a basis for the game, should be built collectively, according to the ARDI method (Actors-Resources-Dynamics-Interactions) (Etienne et al., 2011). We suggest adding a step to the ARDI method: to discuss with the actors how to choose and incorporate the innovations identified in stage C in the game. The results of the game can then be evaluated against evaluation criteria, both the quality of the resource at the basis of the design process, and on the evaluation criteria of the actors involved in the KC stage.

Finally, we suggest the design process itself should be evaluated in two parts: an evaluation of the design process by the participants during the process to enable improvement of the method all along the way; and an evaluation of the capacity of the method to overcome fixation effects, by noting changes in the participants' representation of the design object. Giving participants the time and opportunity to evaluate the method during the process would likely reinforce their involvement and, more importantly, the feeling that their opinions are taken into account in the process, which could help ensure their continuing involvement.

5. Conclusion

We succeeded in creating territorial innovations to reduce the presence of herbicides in a river using a new participatory design method that links socio-technical diagnosis, C-K theory, and serious games. This method increased the relevance of innovations for four main reasons. First, the innovations went beyond the scale of the plot to focus on a territory. Second, they were designed as a coherent system since they were created and thought out simultaneously. Third, they overcame the cognitive biases of agricultural actors who tend to innovate only within their own agricultural sector and at the plot scale. Fourth, serious games made it possible to test these breakthrough innovations in a safe place. This success proves that our new territorial innovation method can help develop efficient strategies to reduce the pollution of a river. We thus recommend the method for use in situations where territorial innovations are needed.

We recommend that innovations reorganise activities at the watershed scale: plot or farm level innovation needs to be coordinated with, for instance, quality labels, shared agricultural tasks, rotational grazing, or regulation of the watershed.

To ensure the success of the new method, we recommend an additional step to reinforce the participatory mechanism with the stakeholders to guarantee their continued participation throughout the key stages of the process. We also recommend adding a participatory step on how to include the breakthrough innovations in the serious game.

Innovations were not the only result of our application of this new method: the method is also the participatory system that combines the design of the territory and the water quality monitoring system. This type of design mechanism could become permanent, for example, in the form of social-ecological research platforms, to capitalize on knowledge on the dynamics of the socio-ecological system while developing collaboration and synergies between the actors concerned.

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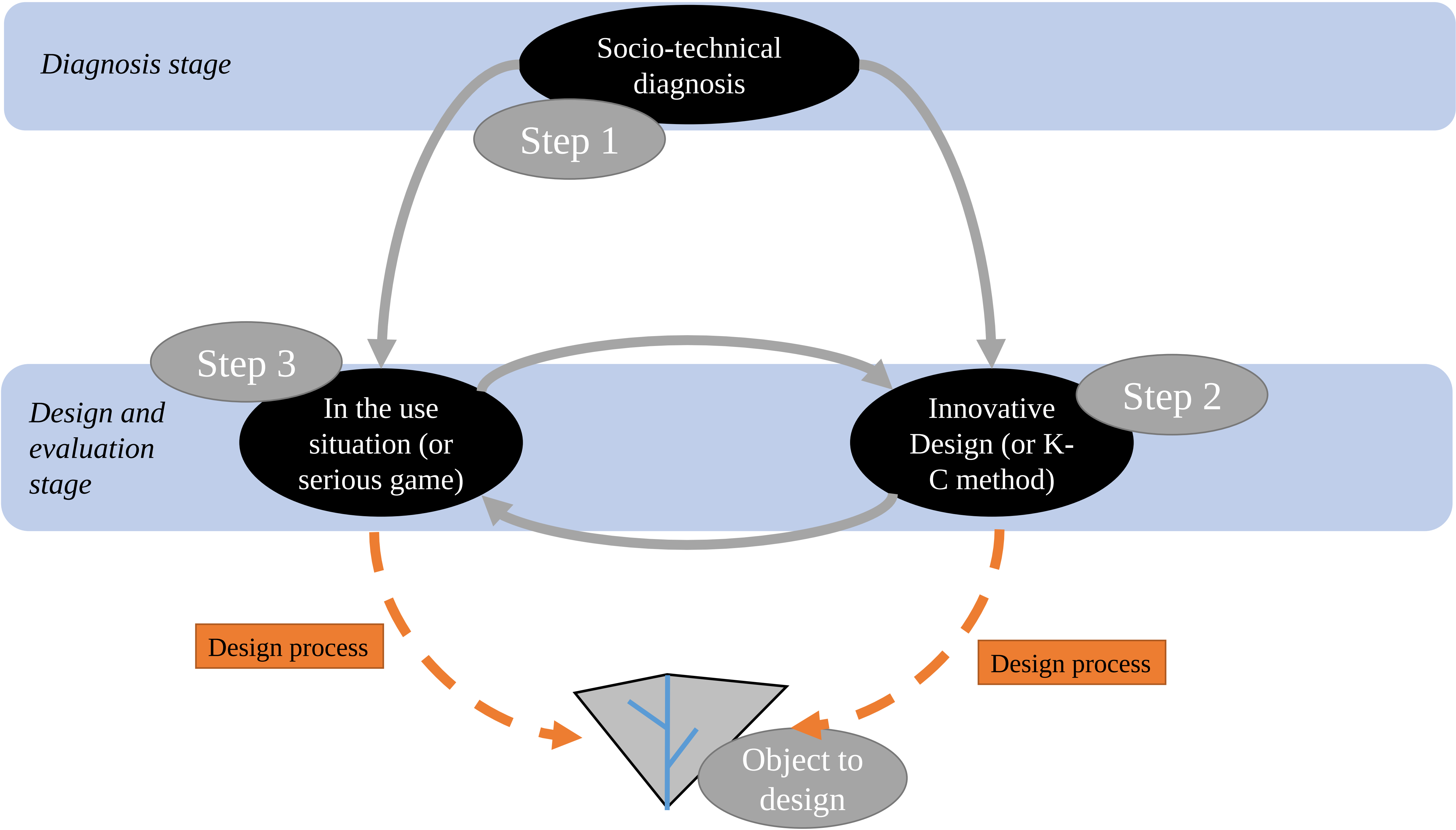
Diagnosis stage
Socio-technical diagnosis
Step 1
Step 3
Step 2
Design and evaluation stage
In the use situation (or serious game)
Innovative Design (or K-C method)
Design process
Design process
Object to design