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Design workshops for innovative cropping systems and decision-support tools: learning from 12 case studies

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Highlights

- Design workshop is a relevant approach to support disruptive innovations design
- A cross-case analysis, fed by design theory, drew lessons to manage design workshops
- Recommendations to prepare and implement a design workshop are suggested
- Diverse methods that avoid fixation effects and support creativity are identified
- The choice of the actors participating to a workshop is a key factor of success
- Ways to consider the systemic nature of agricultural innovations are proposed

Abstract

Addressing the issues that agriculture is currently facing requires disruptive innovations, which may be stimulated through a process of innovative design, enhancing exploration in specific situations. In the aim to equip this process, several researchers implemented 'design workshops'. Yet, the literature poorly describes the way to organize, implement and capitalize design workshops, in the view to achieve their objectives. We conducted a comprehensive cross-analysis of 12 case studies of design workshops, informed both by data on the preparation, course and outputs of the workshops, and by collective interactions among the workshop managers. Steered by theoretical elements from design science, we identified similarities and divergences across cases, and derived methodological lessons

concerning preparation, implementation, and follow-up for future design workshops. Our analysis provides new insights on the key steps for the management of design workshops: key elements to define and share an ambitious but realistic design target were highlighted; the choice of actors participating in the design workshops appeared as a crucial step in the preparation of all the workshops; the initial knowledge basis shared before the exploration had a determinant role on the design process; we identified the need to adapt, to a diversity of agricultural situations, the sequencing, the facilitation of design workshops, and the width of exploration; means to manage, during the design process, the systemic nature of most agricultural innovations were specified; and new criteria, consistent with the diversity of the objectives, were proposed to assess the success of a design workshop. Finally, our research has shown that design workshops promote collective creativity in agriculture, and feed open innovation processes.

1. Introduction

Disruptive innovations are required in agriculture as farmers are expected to increase food supply, save energy and natural resources, strengthen biodiversity, improve soil, air and water quality, and/or decrease the use of external inputs such as pesticides and N fertilizer (Tilman and Clark, 2015; Wilson and Tisdell, 2001). The domains of innovation concerned are widely diverse (Prost et al., 2017): plant varieties and animal breeds; agricultural machinery; inputs, such as bio-pesticides or innovative fertilizers; combinations of farming practices, such as farming, cropping or livestock systems, agricultural landscapes (including crops, grasslands and semi-natural elements like hedges); and decision support systems.

Disruptive innovation towards sustainability entails overarching transformation processes involving technological, organizational, and institutional changes (Geels, 2002). Design, which is a collective process that leads to devising artifacts, that do not yet exist, to attain goals, is at the core of such innovation processes. To achieve the ambitious challenges mentioned above, design enhances the exploration of innovative solutions, unknown until now, that fully satisfy new expectations (Le Masson et al., 2010). Moreover, design in agriculture should be situated, that is, it should fit the solutions to the precise characteristics of the situations of farmers' action, in terms of climate and soil conditions, available means and resources, and institutional and socio-economic contexts (Vereijken, 1997; Darses et al., 2004; Meynard et al., 2012).

This article is dedicated to the design of (i) cropping systems (sets of action rules, related to various and consistent technical choices), and (ii) decision-support tools (action rules related to a specific technical choice, embedded in a manual of digital tool). In these areas, as in the industrial or architectural fields, innovative design cannot be confined to a single approach (Le Masson et al., 2010). Meynard et al. (2012) distinguish three families of approaches. First, step-by-step design consists of an *in situ* gradual change (over several years) of farming practices, based on learning loops and resulting in an innovative system whose characteristics were not predictable at the outset (Meynard et al., 2012; Coquil et al., 2014). Second, model-based design corresponds to a very broad exploration of combinations of techniques and environments, using agronomic models to identify those meeting the desired objectives. It has been used to design cropping and farming systems (Rossing et al., 1997; Bergez et al., 2010), varieties (Jeuffroy et al., 2014), and decision support tools (Cox, 1996). Third, participatory design of prototypes in design workshops, initially proposed in agriculture by Vereijken (1997), brings together actors with a variety of skills (advisors, researchers, farmers, etc.) and knowledge (scientific, expert) on a shared design project targeting challenging objectives (for example, a large reduction in pesticide use, or self-sufficiency in energy). In agriculture, such workshops were implemented to design cropping systems (Lançon et al., 2007; Colnenne-David and Doré, 2014; Lesur-Dumoulin et al., 2018), livestock systems and buildings (Bos et al., 2009; Gouttenoire et al., 2010), decision-support tools (Ravier et al., 2018), and environment-friendly agricultural landscapes (Berthet et al., 2016).

Designing in workshops is a participatory approach adapted to situated collective design, as evidenced by its use (sometimes referred to under different terms, such as workshops, meetings, collective design, design workshop) in many recent studies (Binder and Brandt, 2008; Cardoso et al., 2001; Lefèvre et al., 2014; Lacombe et al., 2018). Based on these studies, we propose to define a 'design workshop' as an approach, in which a collective of actors explores and builds *in abstracto* disruptive solutions to reach ambitious goals. However, while many scientific papers refer to the use of such an approach, with similar intentions, they poorly describe how to prepare and implement the workshops, from the design target definition to the achievement of the design objective. Moreover, some design workshops are centred on the use of computer tools, which strongly shapes the design activity in the workshops, as the prototypes are defined and characterized by the required inputs for the simulation tool used (e.g. Hossard et al., 2013). Therefore, in our analysis, we will not consider such design workshops where design is primarily based on the knowledge embedded in a model: we will only consider the design workshops in which exploration mainly relied on the knowledge carried by all the participants.

Several approaches have been proposed to organize designing in workshops in the agricultural field. The KCP (Knowledge, Concepts, Proposals) method, initially developed in industrial design (Agogué et al., 2014), then adapted to agriculture (Berthet et al., 2015), is structured in three iterative steps: a phase of sharing knowledge (K), intended to encourage dialogue between participants and stimulate their creativity, a phase of concept generation (C), intended to explore innovations; and a proposal phase (P) aimed at developing a roadmap for the continuation of the innovation process. Besides, Reau et al. (2012) formalized a collective approach to design cropping systems: after an agreement between participants on the objectives of the cropping systems to be designed, the group of actors lists the individual crop techniques or crop choices that can be mobilized to reach these objectives, and imagines candidate cropping systems, combining existing or new techniques and crops. These authors show the interest of combining complementary skills among the participants, in particular experts with localized knowledge, experts in innovative techniques, and assessment specialists. In the RIO (Dutch acronym for Reflexive and Interactive Design) method, proposed to redesign animal husbandry systems (Bos et al., 2009), the key starting points are the basic needs of living actors (animals, farmers, consumers). A Brief of Requirements is formulated for each need. This method insists on the importance of taking into account all the needs of the actors involved, instead of weighting the pros and cons of the various interests, which often results in compromises that satisfy nobody.

Yet, none of these approaches informs the many choices regarding the preparation or implementation of design workshops. The scientists who have implemented design workshops, in recent years, hybridized proposals, and invented variants. However, to our knowledge, we miss an analysis and synthesis of these experiences that would support new Research & Development actors wishing to organize design workshops.

This paper aims to: (i) characterize a diversity of ways to prepare and implement design workshops in agriculture, and to manage their outputs and outcomes; and (ii) discuss their advantages and limitations, with a view to drawing methodological lessons and identifying areas requiring vigilance. Our work is based on a cross-analysis of case studies, dedicated to the design of cropping systems or decision-support tools. It aims at helping researchers and actors of the agricultural world to organize design workshops. The authors are researchers who have all conducted design workshops, according to various procedures.

2. Material and methods

We selected 12 case studies of design workshops (described in section 2.2), and we conducted a comprehensive cross-analysis mobilising the C-K theoretical framework (presented in section 2.1). Based on gathered homogeneous information from the case studies (section 2.3), the analysis was performed according to several axes (section 2.4).

2.1. The theoretical framework to analyse the design process in the workshops

To analyse design processes in the workshops, we relied on theoretical advances from the C-K framework (Concept-Knowledge, Hatchuel and Weil, 2002; 2009). According to this theory, an innovative design process is a collective process starting by the formulation and share of a design target, which is a “desirable unknown”: as what exists is insufficient to reach the designer’s goals,

something new needs to be generated (which is desirable), but the designers do not yet know what (it is unknown). During the design process, the identity of the new object under design, corresponding to the designer's desire, is progressively defined, i.e. its properties progressively emerge: its components, the use that can be made of it, by whom, when, in what conditions, and so on. As Hatchuel and Weil (op. cit.) have shown, design is an exploration process, strongly linked to the designers' knowledge and learning. The C-K theory has formalized how the identification of useful knowledge both feeds into, and emerges from the specification of the properties of the innovation under design. Design is therefore described as a dialogue between two spaces, both of which expand throughout the design process: the 'concept space' (or 'solution space'; i.e. what the designers want to make exist), and the 'knowledge' space (i.e. what is known by the designers, and key knowledge gaps regarding the innovation under design). The C-space is structured according to various exploration paths. The K-space refers to explicit knowledge, such as biophysical processes within the agroecosystem, but also to tacit knowledge, to criteria regarding the assessment of the designed solutions, or even to characteristics of the farmers' action situation. As the design targets are new (Le Masson et al., 2010), neither the required knowledge nor even the specifications of the solution under design can be precisely defined at the beginning of the design process, and they become clearer as the innovation under design is taking shape. Innovative design requires not only creativity, but also the capacity to make progressively evolve the fields of knowledge, and the collaboration to be mobilized, while the solutions designed become clearer. Numerous studies on the creative part of design have highlighted that people often explore a small number of unvaried solutions (what's called 'fixation effect', Jansson and Smith, 1991), and that, as a result, methods have specifically been proposed to overcome this fixation effect (Agogué et al., 2014). Jeantet (1998) has furthermore shown that designers frequently mobilize intermediate objects, defined as *"objects generated or used during the course of the design process (texts, graphs, models, mock-ups, etc.), serving as brokers, as traces and supports of the project being pursued, and of the design action"*. Moreover, involving users very early in the process helps to bring out the adaptation to their own situations of (i) the design target, (ii) the characteristics of the solutions to be designed, and (iii) the criteria used for the evaluation of the solutions under design (Luck, 2007; Bos et al., 2012; Cerf et al., 2012).
This theoretical framework helped us (i) to organize data collection from the case study managers (see section 2.2) and (ii) to define the axes for the cross-case analysis (see section 2.4).

2.2. Criteria used to choose the case studies

We conducted a comprehensive cross-analysis of 12 design workshops (Table 1) to identify the convergences and divergences between these case studies, in order to draw methodological conclusions

(Yin, 2003). The 12 case studies were selected from more than 20 design workshops conducted by the authors of this article, between 2008 and 2018. Four criteria were used to select the case studies:

(i) All the selected design workshops focused on the design of ways to grow annual field crops. The designed solutions were either a decision-support tool (DST), or one or several cropping systems (CS).
(ii) The facilitators of the design workshops were all researchers with design experience. They knew the design literature, which inspired them to prepare and facilitate the workshops.
(iii) The selected case studies covered a wide range of actors involved in the design workshops, and of the duration of the project (from a few weeks to three years, Table 1).
(iv) At least one of the facilitators of each design workshop agreed to provide information about it. Hereinafter referred to as the "case managers", they are all co-authors of the present article.

The 12 case studies addressed a variety of issues (Table 1) related to the agroecological transition, formalized either by constraints on practices, or by new ecosystem services to be promoted: pesticide-free management (3 case studies), reduction of N-fertilizer inputs (2 case studies), cropping systems diversification through various crops or cultivar mixtures (3 case studies), climate change mitigation (3 case studies), and work organization (1 case study). In all case studies, systemic solutions were designed: sometimes situated (for example, a cropping system for a specific farm), sometimes more generic (Decision-Support Tools, *a priori* usable by any farmer, or generic cropping systems for a type of farm in a given region). Another common feature of all workshops was the involvement of future users of the designed solutions. In many cases, the outputs of the design workshops were operational (Table 4): cropping systems designed to be tested in experiments (SDCI, AGROSEM, SIC), or implemented by farmers (AUTO'N); DSTs designed to be developed and disseminated to support a decision improving the management of cropping systems (APPI-N, CAPS). A detailed presentation of the 12 case studies is provided in supplementary material.

Table 1: Characteristics of the 12 design workshops selected as case studies (CS: Cropping system; DST: Decision-Support Tool)

Project name	Designed innovations	Involved actors *	Organisation
AGROSEM	Pesticide-free seed-oriented CSs	6 experimenters, 2 R&D engineers, 3 researchers	3 meetings over 9 months
AUTO'N Guillier et al., 2020	Nitrogen-autonomous arable CSs for farmers	7 farmers and 3 experts	7 meetings (1 per farmer) over 1 year
CONSYST Ferchaud et al., 2020	Arable CSs including crops intended to feed a biorefinery	3 researchers and 4 R&D engineers	2 meetings (1 per soil type), over 6 months
LEGITIMES Pelzer et al., 2020	CSs including more legume crops within three territories	8 to 13 local actors or innovation leaders, according to territories: 1 to 2 farmers, 3 to 5 advisors, 2 to 5 researchers	3 one-day meetings (1 per territory) over 2 months
SDCI Reau et al., 2012	Pesticide-free CSs, adapted to various specific areas	5 to 10 actors per meeting (advisors, R&D engineers, researchers)	1 meeting per area, over 3 years
SIC Colnenne-David et al., 2017	Arable CSs limiting GHG (greenhouse gas) emissions	10 actors per meeting (advisors, R&D engineers, researchers)	2 meetings, over 6 months
SYSCLIM Angevin et al., 2016	Arable CSs with low GHG emissions, within a collecting area	At each meeting: 3 researchers, 1 to 2 advisors, 1 collector, 6 farmers	2 meetings (1 per zone) over 3 months
VIVLEBIO Salembier, 2019	Innovative strategies to manage perennial weeds in Organic Farming	8 farmers, 2 advisors	1 meeting
APPI-N Ravier et al., 2018	A DST to manage wheat N fertilization while tolerating N deficiencies	5 researchers, 3 R&D engineers, 3 advisors	2 meetings over one year
CAPS Paut et al., 2021	A DST to help choose the companion species to grow with rapeseed according to the ecosystemic services targeted	3 researchers and 7 advisors	2 meetings over 7 months
CASABIO Hazard et al., 2016	Rules to mix wheat cultivars in Organic Farming	6 to 10 actors per meeting: 8 researchers (agronomists and geneticists), 1 farmer and 5 R&D engineers	2 thematic meetings (N and weeds) over one month
DST-WORK Delecourt et al., 2019	A DST to take into account work in the change of practices	First meeting: 8 farmers, Second meeting: 5 advisors and R&D engineers	2 meetings over 3 months

* In addition to the one or two facilitators present in all the workshops

2.3. Information collected on the 12 case studies

For each of the 12 case studies, we collected information from the case managers, through (i) written documents on the case studies (workshop reports, articles, PhD theses, dissertations); (ii) an oral presentation of each individual case study by the case manager in front of the group of all case managers; and (iii) collective interactions within this group, during 3 collective work sessions. The presentations were organized in such a way as to answer a series of open-ended questions, aimed at acquiring homogeneous data on the course and outputs of the design workshops, and their preparation and implementation modalities (Table 2). More specifically, the questions focused on: (i) the chronology of events (steps, results, choices made by the case managers, etc.); (ii) the reasons that justified the choices made; and (iii) an argued assessment, by the case managers, on the course and outputs of their own design workshops. These questions were chosen on the basis of the theoretical framework presented above (e.g. How did you manage the formulation of the design targets? How did you stimulate exploration and creativity?). Following each of the 12 oral presentations, exchanges between each case manager and the whole group made it possible to complete the data collected from the presentation and to start comparisons. The cross-case analysis began during the collective discussions following the presentations, and was based on iterations between the analysis of each case and cross-analyses, aiming to bring out and categorize convergences and divergences between cases.

Table 2. Questions to the managers of the 12 case studies, to inform an oral presentation and collective interactions

General questions on the course of the design workshops and their outputs

- Why did you decide to organize this design workshop?
- According to you, what were the factors explaining the success or failure of the design workshop?
- What were outputs and outcomes of the design workshop?

Questions related to the preparation of the design workshop

- What type of innovation were you planning to design during the workshop (e.g. a cropping system, a decision-support tool)?
- How did you choose the actors to be invited to the design workshop? Who were these actors? What arguments did you use to enrol them?
- How did you manage the formulation of the design targets? What were these targets?
- How did you choose the knowledge to be shared at the beginning of the design workshop (and what consequences on the following design step did you observe)?

Questions related to the implementation of the design workshop

- How did you manage the design of systemic solutions during the workshop?
- Did the workshop last more than one day? If so, what was the temporal organization of the successive meetings? What was the design progress from one day to the next? How was the design organized on the successive days?
- What balance did you decide to strike between exploring a large number of ideas and deepening an exploration path? Why did you decide to do so?
- How did you stimulate exploration and creativity? What did you do to reduce the fixation effects among participants?
- Did you use intermediate objects during the design workshop? If so, which ones and to what purpose(s)?
- Have these intermediate objects been remobilized in other design workshops or do you think they should be specifically built *ad hoc* for each workshop?

2.4. Axes for the cross-case analysis

The theoretical framework presented above allowed us to identify the commonalities and differences between the 12 case studies, concerning the preparation of the design workshops, their implementation, and their outputs and outcomes (Table 3). The analysis is based on a collective reflection among the workshop managers.

The preparation of the workshops was analysed according to 4 axes, which emerged from the inductive cross-case analysis (e.g. the sequencing of the meetings) or have been chosen in coherence with the key dimensions of the *C-K theoretical framework* described in section 2.1 (and identified in italics below):

(i) Design target: we compared the nature and formulation of the design targets, corresponding to the *desirable unknown*, shared among the participants. We categorized these targets according to what they aimed to explore and how they were formulated.

(ii) Actors participating: we registered the reasons, given by the case managers, for choosing the *actors invited to participate* in the design process.

(iii) Knowledge shared: we classified the nature of knowledge that has been shared at the beginning of the workshop, *as an initial K-space basis*.

(iv) Sequencing of the meetings: as the "design workshop process" included several meetings in some case studies, we compared their numbers, roles and frequencies.

Then, the analysis of the implementation of the design workshops was organized along 4 axes:

(i) Width of the *exploration*: we compared the variety of solutions that had been explored during the workshops, in the aim to characterize and assess the *explored C-space*.

(ii) Management of systemic design: we analysed the means used during the workshops to progressively build systemic solutions.

(iii) Intermediate objects: we identified the various roles of the *intermediate objects* used during the workshops to foster the design process.

(iv) Modalities of facilitation: we classified the different objectives and related actions performed to facilitate the design process, with a particular attention to the levers used to *reduce fixation effects* and *stimulate creativity*.

Finally, we mapped the outputs and outcomes of the design workshops and compared them to the initial objectives of the case managers: *solutions designed*, *knowledge mobilized* during the workshop, test in real conditions.

Table 3 : Key axes, mainly derived from C-K theoretical framework, of the cross-case study analysis of design workshops steps: preparation, implementation, and outputs

Key steps of design workshops	**Key axes for the cross-case analysis**	**Key dimensions of the theoretical framework serving as bases (see section 2.1)**
Preparation	• formulation of the design target • choice of the invited actors • choice of knowledge to be initially shared • sequencing of the meetings	• Defining the “desirable unkown” • Collective dimension of the design • sharing a knowledge basis to initiate and stimulate the exploration process (part of the K-space) •
Implementation	• width of the exploration • management of the systemic nature of the solutions under design • intermediate objects used • aims and modalities of facilitation	• characterizing and assessing the C-space that was built through exploration of unknown solutions • • intermediate objects intended to support the design process • overcome of fixation effect (usually observed)
Outputs and outcomes formalization	• formatting and sharing the solutions designed and the knowledge mobilized during the workshop, or lacking to reach the target	•

3. Results

3.1. Preparation of the design workshop

In most cases, the preparation of the workshop required a significant investment of time over several days.

3.1.1. Formulation of the design target

All case managers defined disruptive, ambitious, forward-looking, but realistic targets, *i.e.* likely to lead to innovative solutions (Table 4): for example, the removal of pesticides within conventional cropping systems (SDCI, AGROSEM), or a 50% reduction of greenhouse gas emissions, compared to the dominant CSs (CONSYST, SIC).

Different rules were used to define the targets, with a view to stimulate the participants' creativity and avoid fixation effects: (i) proposing an oxymoron (e.g. "living in harmony with thistle" for VIVLEBIO); (ii) defining a target that is out of step with current or recommended practices, or even free of regulatory constraints (e.g. "to fertilize without defining a target yield" for APPI-N); (iii) introducing a strong constraint on the inputs that can be mobilized (e.g. "no use of mineral nitrogen fertilizer", for AUTO'N; or "seed production systems without pesticides", for AGROSEM); (iv) prioritizing a formulation based on the expected results rather than on the means. Table 5 summarizes all the methods used in our case studies to avoid fixation effects and stimulate creativity.

In some cases, a specific work was carried out beforehand to define the target. For example, in the case of APPI-N, a diagnosis of uses of the tools formerly available to manage nitrogen fertilization was carried out through interviews (Ravier et al., 2018). The frequent difficulties encountered by the users of the 'dominant' tool, the balance-sheet method, concerning the choice of the target yield (which is a key step of the method), led to the proposal of a disruptive target: "to fertilize without defining a target yield". In the case of VIVLEBIO, the results from previous on-farm innovation tracking, showing that some innovative farmers tried to value thistles in their fields, led to the proposal of a target which did not entail their withdrawal. In the AUTO'N case, the target was defined before the workshop, through bilateral discussions between the workshop facilitator and the farmers, focusing on an in-depth analysis of their motivations in terms of nitrogen management. However, even though farmers generally expressed several indicators for their expected results, it appeared, in this case study, that starting a workshop with a precise and complete definition of a framework of objectives and constraints tends to block the thought of participants, and seems less generative than a definition of a target centred on the most challenging criteria. Similarly, defining a distant target, *i.e*. to be reached only in several years, was essential to help the designers to leave aside immediate feasibility constraints that hamper creativity (APPI-N, AGROSEM, CONSYST, LEGITIMES, CAPS, DST-WORK case studies).

Several case studies confirmed that it was essential for the target to be shared by the actors participating in the design workshop, in order to foster a collective exploration. In the case of SYSCLIM, the frequent warnings of some participants (the collectors) about the risk of reducing the harvested grain volume ("we need to fill the silos") indicated that the target focused on reducing GHG emissions did not take into account their concern about the level of production. In the case of CASABIO, the case manager identified another difficulty: the target was very broad ("to reduce weed pressure") and the lever explored (rules for wheat cultivar mixtures) was too narrow, which prevented the workshop from reaching its target. On the other hand, in several case studies (APPI-N, VIVLEBIO, SIC, DST-WORK), the case managers stressed the importance of the time devoted, at the beginning of the workshop (knowledge sharing, § 3.2.3), to the participants' appropriation of the target.

Table 4: Description of the targets, and of the outputs that were targeted or not, for each case study

Project name	Target(s) formulation	Outputs that were targeted	Outputs achieved whereas not targeted
AGROSEM	Rotation, crop management and landscape infrastructure for annual seed-oriented crops (cereals, legumes, vegetables, forage crops), without pesticides.	CSs reaching the target, implemented in trials.	Learning to think 'out of the box' and to enhance systemic reasoning, for partners.
AUTO'N	One N-autonomous CS per farmer Example: Eliminate the purchase of mineral nitrogen fertiliser, while ensuring the absence of economic losses due to nitrogen deficiencies.	CSs more self-sufficient in synthetic nitrogen, implemented by farmers.	Mutual support between farmers (e.g. to implement ambitious and feasible systems, or even to cultivate a new species).
CONSYST	CSs that reduce net GHG emissions by 50%, increase the biomass produced and exported, and maintain the feeding capacity (do not degrade it by more than 20%), compared to current CSs (i) in deep silty soils, and then (ii) in shallower silty sandy soils.	CSs reaching the target.	A learning process about the possible levers to adjust flexible CSs.
LEGITIMES	CSs including a diversity of legumes and species, and limiting the risks of pests, weeds and diseases, and nitrogen losses to the environment.	High-performance CSs including legumes, and the adaptation of the management of the other crops, in each territory.	A dynamic between actors was created, which was useful in a later stage aiming at implementing territorial actions for the development of legumes.
SDCI	CSs without pesticides (in a first step), and then with few pesticides, and controlling weeds, pests and diseases.	CSs reaching the target, implemented in on-farm field experiments.	Learning for advisors to think 'out of the box' and to enhance systemic reasoning.

SIC	A CS aiming to reduce GHG emissions by 50%, and to meet several environmental objectives while being productive.	A CS that reaches the target and implemented in the SIC trial.	
SYSCLIM	Alternative CSs adapted to the local context, designed to mitigate the effects on global warming and improve their contribution to sustainable development.	Original CSs, compared to those practised by the farmers participating in the workshop.	Show to the collector that alternative CSs were possible.
VIVLEBIO	Cropping strategies to live in harmony with thistle, including CSs without alfalfa and without tillage.	A set of strategies for living with thistle; a collective willingness of participating farmers to go on working together on this target.	Research questions of interest (e.g. when does the thistle begin to wither if its density is high? Why do various thistle plants react differently to similar practices?)
APPI-N	A N-fertilization method without yield target (for the 2nd meeting: idem + taking into account the risk of drought to maximize the efficiency of fertilizer use).	A prototype of DST reaching the targets.	The creation of new scientific knowledge (e.g. NNI path avoiding detrimental deficiencies).
CAPS	A DST helping to select species to mix with oilseed rape providing several ecosystem services and based on the causal chain "trait-function-service".	A prototype of DST, capitalizing on empirical knowledge.	
CASABIO	Rules for the mixture of wheat varieties to reduce weed pressure and/or nitrogen deficiencies in Organic Farming.		A knowledge tree to identify technical and genetic levers toward the target.
DST-WORK	A DST to help farmers: (i) to think about the introduction of a new technique before experimenting with it; (ii) to analyse the results of their experiment, and adapt their work organization.	A portfolio of 30 conceptual mock-ups for a DST meeting the target.	A large range of unplanned ways to consider work in the dynamics of change on a farm.

3.1.2. Choice of the actors participating in the design workshops

In most case studies (Table 1), the facilitators called upon actors with diverse expertise (e.g. advisors, farmers, researchers) and from various professional structures (e.g. chambers of agriculture, research institutes, technical institutes, agricultural cooperatives). Case managers justified this diversity with several motives:

- Enhancing creativity through the confrontation of different points of view: e.g., in the APPI-N case study, the facilitators took care to mix (i) actors developing and supporting the most used method (balance-sheet method) with actors claiming an alternative way to improve fertiliser management; and (ii) actors who are familiar with farmers' decision process, researchers studying nitrogen flows in the agroecosystem, and engineers skilled in formalizing and disseminating technical advice (see Table 1).
- Ensuring the participation of actors with general knowledge (agronomists working on bio-physical processes within the agroecosystem), and actors with local knowledge on agricultural conditions and farmers' work situations (e.g. engineers, advisors and farmers from the study region, in CONSYST, LEGITIMES and SDCI case studies).
- Involving future users of the designed solution (e.g. farmers for CSs, and/or advisors for DSTs). When the design workshop aimed to produce cropping system prototypes to be experimented, the facilitators considered the experimenters' presence as essential to guarantee the acceptability of the designed solution (e.g. AGROSEM and SIC case studies), even if sometimes they were too much fixed on solutions they already knew.

In contrast, in a few other case studies, the design workshops brought together only actors sharing the same profession (only farmers for AUTO'N, SYSCLIM, and DST-WORK 1st meeting; only advisors for the DST-WORK 2nd meeting). The aims were (i) to foster peer-to-peer sharing of similar concerns, (ii) to avoid fixation effects linked to farmers' dependency on the 'good agricultural practices' recommended by their advisors, and (iii) to ease structure the discussions. Besides, some case managers observed that a large exploration was easier to achieve when the main users of the solution to be designed were not involved, as they considered insurmountable their daily-experienced constraints. Thus, in the case of AUTO'N, the 'central' farmer, for whom the cropping system was designed, did not participate in the exploratory phase. He only presented the situation of his farm at the beginning of the meeting, and, at the end of the meeting, he discussed and further developped the solutions proposed by the other farmers.

In all cases, the case managers stressed that they selected people who were motivated to change their agricultural practices, and were *a priori* open to new solutions, to avoid participants which could act as 'floaters' or 'blockers'. For example, in DST-WORK, based on prior interviews, the facilitators decided not to invite an actor who seemed set on his own solution. The prior inter-knowledge of the actors was taken into account in several workshops. For APPI-N, actors belonging to the same organization and with hierarchical relations between them were accepted, as they had freedom of speech allowing fruitful discussions. By contrast, in DST-WORK, the participants in the first workshop were a group of farmers with their advisor. The presence of the advisor seems to have hindered the farmers' contribution to the discussions, as they were afraid of proposing solutions that were inconsistent with the recommendations previously given by their advisor.

Finally, in some design workshops, a particular role was assigned to some participants. For example, in the CONSYST case study, a researcher was in charge, during the workshop, of calculating indicators such as food production or GHG emissions, in order to assess, in real time, the options explored, and give preference to those that seemed most promising or, on the contrary, eliminate others.

3.1.3. Choice of the knowledge to be shared

In all the design workshops studied, a knowledge-sharing phase preceded the collective exploration phase. It required significant preparation from the workshop facilitators, and sometimes gave rise to specific prior research. The nature of the shared knowledge varied according to the targeted aim:

- Share a same vocabulary, or even become familiar with the design issue. Thus, in the LEGITIMES case study, the benefits and limitations of legumes were presented, varying according to species and modes of insertion in cropping systems (as a pure crop, intercropped with another crop, as a cover crop, etc.).
- Share a diagnosis of the current situation. In the LEGITIMES and SDCI case studies, the current most prevalent cropping systems in the territories under study were described, including their limits in terms of agronomic and environmental impacts, taken as a starting point for design. In the AUTO'N case study, the 'central' farmer presented his farm, his unsatisfactory results, or his new targets. In the DST-WORK and APPI-N case studies, the results of diagnoses of uses, conducted as a specific prior research (Ravier et al., 2016; Delecourt et al., 2019), were presented at the beginning of the workshop with the aim to go beyond fixation effects (see Table 5). For APPI-N, these results showed that a key principle of the balance-sheet method, i.e. estimating the crop requirements by a target yield, was a barrier for the users. Sharing this diagnosis allowed the participants to adhere to the proposed ambitious design target (a N-fertilization method without yield target).
- Share a common representation of the processes involved in the agroecosystem functioning. In the CAPS case study, the "Traits-Functions-Services" conceptual framework (Violle et al., 2007) was presented. Similarly, in the VIVLEBIO case study, a literature review (Favrelière et al., 2020) was synthesized to present the studied crop techniques able to control thistle, in relation to its biological

characteristics. In the SYSCLIM case study, the biophysical processes involved in GHG emissions were presented.

- Enhance creativity: disruptive examples were sometimes presented to stimulate creativity (see Table 5). For example, in the VIVLEBIO case study, the results of an on-farm innovation tracking, highlighting innovative practices implemented by farmers to control thistle, completed the literature review mentioned above (Salembier, 2019). In the AGROSEM case study, the results of previously tested pesticide-free systems in arable farming, describing the technical options implemented and their effectiveness to control pests, were presented.

When the design workshop was composed of several meetings, the presentation, at the beginning of the second meeting, of the assessment of the prototypes designed at the first one (CONSYST and APPI-N case studies), or of the knowledge generated since the previous meeting (Nitrogen Nutrition Index path avoiding detrimental deficiencies, in the case of APPI-N), were crucial for the design progress.

In some case studies (LEGITIMES, CAPS, CASABIO), the presentation of technical options allowing the chosen target to be reached may have limited the participants' creativity by 'fixing' them on already existing solutions. For example, in LEGITIMES, during the first two meetings, the advantages of legume-based mixtures were presented in detail, and this technique was then largely mobilized by the participants in the CSs designed. During the third meeting, this focus was mitigated, as the knowledge sharing phase was positioned after a phase of individual reflection and proposals. This limitation was less frequently encountered when the shared knowledge focused on agroecosystem biophysical processes, and only mentioned technical levers as options influencing these processes (AUTO'N and SIC case studies).

3.1.4. Sequencing of the meetings

In most case studies, design workshop processes included several meetings (Table 1), and the facilitators had to organize their articulation, upstream or *in itinere*, considering the results of the previous meetings. Across all case studies, three types of sequencing were identified:

- A successive exploration of situations: in the CONSYST and SYSCLIM case studies, two meetings were organized with the same target, on two different soil types. Similarly, in the LEGITIMES case study, locally-adapted cropping systems were successively designed for 3 territories, characterized by different pedo-climatic and socio-economic contexts (better adapted legume species, outlets, presence of livestock, etc.), while keeping a common design target. Lastly, in the AUTO'N case study, 7 meetings were organized to design cropping systems for 7 farmers.

- A progression in the target: in the SDCI case study, the first target proposed was very ambitious (e.g. manage pests without pesticides) to encourage participants to propose very disruptive technical options; then, in the following meeting, a less ambitious target was formulated (e.g. manage pests by reducing pesticide use by 50%) to propose more realistic cropping systems intended to be tested in trials. Consistently with the target evolution, the assessment criteria changed: economic criteria, which are decisive for realistic systems, were not put forward at the beginning of the exploration of disruptive systems, but appeared at the end.
- A progression in the designed solutions: in the AGROSEM case study, the facilitators planned a series of meetings to deal with objects of increasing complexity. The first meeting was dedicated to the design of herbicide-free crop management for a seed-oriented carrot, while the second meeting combined the design of the crop rotation and of the zero-pesticide management of the other crops. The third meeting was mainly dedicated to landscape infrastructures. The choice, in the first meeting, of designing a rather simple object (withdrawal of only herbicides from only one crop) aimed to teach the participants to be less fixed on known solutions, and to make them adhere to the design workshop principles.

Sometimes there was a long interval between two meetings, allowing the realization of specific activities necessary for the organization of the following meetings: e.g. multi-criteria assessment of cropping systems designed, in the CONSYST case study; parameterization of the Nitrogen Nutrition Index (NNI) threshold path, in the APPI-N case study; literature analysis to inform a database of species traits, in the CAPS tool. However, some case managers mentioned that too much delay between two meetings (such as in SDCI case study) had affected the overall dynamics of the design workshop.

3.2. Implementation of the design workshop

3.2.1. Broad exploration or deepening of some paths

The design workshops organized the exploration phase to favour, depending on the case study, either a wide range of solutions (CASABIO, LEGITIMES, DST-WORK, VIVLEBIO, SYSCLIM, and SIC case studies), or the deepening of a small number of solutions (CAPS, APPI-N, AUTO'N, SDCI, and CONSYST case studies).

Concerning DSTs, the choice between diversity and refinement depended on the time available, and on the targeted outputs. Thus, in the case of APPI-N, conducted during a PhD thesis, the objective to have an operational prototype of the tool by a set date led to focus on the deepening of one of the paths opened during the first design meeting. This deepening made it possible to generate the necessary knowledge, to create the prototype, and to test it in on-farm conditions, during a PhD of 3 years (Ravier et al., 2018). By contrast, in DST-WORK case study, as the problem was new and had received little attention in plant production research (Delecourt et al., 2019), a broad exploration was given priority. The same type of contrast was observed for the design of cropping systems. When the targeted output of a workshop was new practices to be implemented by a participant, either farmer or experimenter (AGROSEM, AUTO'N, SDCI case studies), the diversity of the paths explored was restricted, and preference was given to finding rapidly implementable solutions. Conversely, in a framework less constrained by time, or with no intent for rapid implementation, the exploration was broader (SIC, VIVLEBIO, LEGITIMES, SYSCLIM case studies). In some design workshops, both objectives (broad exploration and deepening of some paths) were targeted, and achieved by organizing a complementarity between successive meetings within the same project (e.g. in LEGITIMES, the feasibility of some designed CSs was discussed with the actors during a second meeting, and changes were proposed to make them more "feasible"; see Pelzer et al., 2020).

3.2.2. Ways to design systemic solutions

In all workshops, the designed solutions were systemic (Table 1). For example, in the AGROSEM case study, reducing pest pressure on wheat, and thus pesticide use, is reached through managing interactions between variety, sowing density, nitrogen fertilization and sowing date, as proposed by Loyce et al. (2008). Similarly, in the APPI-N case study, the targeted increase in fertilizer use efficiency depends on the interaction between the use of a NNI threshold path – which helps to determine deficiencies that will not be detrimental to yield –, and a weather criterion for choosing the application date, i.e. before rainfall to facilitate the diffusion of the fertilizer into the soil. In the AUTO'N case study, designing self-sufficient CSs required nitrogen to be managed by combining proposals for three timeframes: (i) the short timeframe aimed at sufficient nitrogen nutrition throughout the crop cycle; (ii) the intermediate timeframe of the crop sequence, a key to manage nitrate losses; and (iii) the long timeframe for organic nitrogen storage in the soil.

In most workshops dedicated to CSs design (SDCI, CONSYST, AUTO'N, VIVLEBIO case studies), the exploration was organized in two successive phases: the first one aimed at designing the crop sequence, and the second one concerned the management of each crop. However, during the second phase, the participants often had to reconsider the choice of crop sequences, to value the interactions between crop management and crop sequence in the view to reach the design target. Therefore, facilitators of some design workshops chose to split the cropping system to be designed into sub-systems, which were believed to be 'easier to handle' during the exploration process. They then organized an information feedback loop between these successively designed sub-systems throughout the exploration phase. This was the case of AGROSEM, in which facilitators organized a feedback loop between the design of the crop sequence and the management system of each crop (see section 3.1.4). In the LEGITIMES case study, an individual reflection phase aimed at proposing short crop sequence patterns (involving 2 to 3 crops) including at least one legume crop, mainly focusing the collective exploration phase on the combination of these 'bricks'. Conversely, in the CASABIO case study, the separate exploration, in successive and independent meetings, of the management of nitrogen and weeds (that farmers considered to be independent), made it impossible to design rules for choosing variety mixtures allowing control of these two major limiting factors in Organic Farming

3.2.3. Intermediate objects used during the design workshops

In all design workshops, different intermediate objects were used for three purposes: to stimulate creativity and/or reduce fixation effects; to build the emergence of systemic effects; and to assess the selected options.

Firstly, various intermediate objects enhanced the exploration of new options, helping to overpass fixation effects (see Table 5). In several case studies (e.g. SIC, VIVLEBIO, AUTO'N), the presentation to the participants of an exploration tree summarizing the ideas resulting either from a first phase of exploration, or from previous work by the facilitators, made it possible to refine the exploration and guide it towards new paths. In the APPI-N case study, the presentation of a "martyr" prototype of the Decision-Support Tool highlighted several original required characteristics, and allowed participants to challenge its particularities and to propose alternatives.

A second type of intermediate object was proposed to support a systemic design by sharing the visualization of interactions. In the CASABIO case study, a tree synthesizing the available knowledge on strategies and practices to achieve the objectives (weed control or crop nitrogen nutrition) was presented and served as a support for discussion on the levers to be combined. In the AGROSEM, CONSYST, and SDCI case studies, a diagram showing the chronology of the individual technical actions resulting from a previous meeting supported the consideration of temporal concordances in the designed cropping systems. In the AUTO'N case study, a dedicated board game was also used, serving to manipulate the various components of the cropping system (crop sequence, synthetic and organic fertilization actions, catch crops), and to continuously visualize their interactions, in order to build a consistent cropping system.

Finally, a third type of intermediate object was used in some workshops to assess the explored options. Thus, during the meetings of the CONSYST case study, a calculator of assessment indicators was used to perform a simple and quick evaluation of the proposed options, in order to sort them and to deepen the exploration of the most interesting ones.

3.2.4. Aims and modalities of the workshop facilitation

In all case studies, the facilitation had several objectives. The first one was to manage the systemic nature of the solution under design, a necessity for reaching ambitious performance. In all design workshops, the facilitator encouraged the participants to combine the proposed concepts coherently, thereby putting the systemic characteristics of the designed innovation at the centre of the design process.

The second aim was to stimulate and facilitate collective discussions during the exploration phase. In all case studies, the facilitator encouraged benevolence and trust between participants, and the creation of a group dynamics. For several design workshops, a major objective of the first meeting was to make participants want to come back, as design could not be ended in a single one (e.g. VIVLEBIO, AGROSEM, AUTO'N, APPI-N, and LEGITIMES case studies).

The third aim was to limit the participants' fixation effects, and to stimulate their creativity (Table 5). Several facilitators mobilised tricks during the exchanges to get participants to think differently from usual, and be creative: (i) stating a property for the innovative system, which is contrary to that usually known (e.g. a crop that is always well supplied with N vs. a crop that tolerates nitrogen deficiencies, in the APPI-N case study); (ii) working from a known solution, by formulating the properties that characterize this solution, and exploring variants of these properties (VIVLEBIO and CASABIO case studies); (iii) temporarily removing constraints: in the SDCI and SIC case studies, while the aim was to design profitable pesticide-free cropping systems, removing the profitability constraint made it possible to explore less remunerative species to lengthen the crop sequence, and then, in a second stage, to recover good profitability thanks to the cost savings they allowed on the crop sequence; (iv) encouraging the participants to clarify the underlying knowledge for each proposed option (in most case studies): this clarification often led to a new idea, which then became a new solution, thus contributing to enrich the exploration.

The facilitation also aimed to help participants situate themselves in the solutions space under construction. As the discussions between participants were often very quick, it was generally not possible to write down the main ideas and the underlying knowledge, so as not to break the dynamics of the interaction. Nevertheless, in some design workshops (AGROSEM, APPI-N, and VIVLEBIO case studies), the facilitator sometimes temporarily stopped the discussion to help the participants to take a step back from the ongoing design process: the facilitator summarized the discussion by identifying that a new property of a solution, or a new evaluation criterion, had just been proposed. Sometimes, he/she redefined an option by specifying the concept and the underlying knowledge, or pointed out that the proposal opened a new exploration path.

The facilitators mentioned the tricks they used to deal with an heterogeneous collective of designers: (i) using a time for individual reflection ('sticky notes sequence') to force every participant to make proposals, which encouraged everyone to speak afterwards and avoid ‘floaters’; (ii) never allowing the floor to be monopolized by a single participant; (iii) never allowing certain solutions to be imposed (for example, those that had already been tested or implemented by some participants), or to be discarded without debate, but always stimulating the exploration of new solutions. In some design workshops involving farmers, advisors and researchers, the facilitator had to deal with a lack of exploration. This stemmed from the fact that many farmers adopted a posture inherited from the classic top-down model of R&D in agriculture, where they waited for researchers or advisors to propose options that they can then apply (e.g. SYSCLIM and DST-work case studies).

Table 5: Summary of the methods used in the case studies to avoid fixation effects and stimulate creativity, with mention of the corresponding paragraphs of the Results section, the concerned case studies, and some references citing the methods.

	General principles to avoid fixation	**Section**	**Case studies**	**References citing this principle**
Preparation of the design workshop	Adopt a disruptive and ambitious target (oxymoron, loosening constraints, prioritizing a formulation based more on the expected results than on the means)	3.1.1	AGROSEM, AUTO'N, CONSYST, SDCI, SIC, SYSCLIM, VIVLEBIO, APPI-N	Agogué et al., 2014; Hatchuel and Klasing Chen, 2017, Brun, 2019
	Choose diverse and open-minded participants	3.1.2	CONSYST, LEGITIMES, SDCI, APPI-N, CAPS	Reau et al., 2012; Ravier et al., 2018; Vourc'h et al., 2018
	Share disruptive knowledge (i.e. innovative examples, generated by on-farm innovation tracking or diagnosis of uses)	3.1.3	AGROSEM, LEGITIMES, VIVLEBIO, APPI-N, DST-WORK,	Agogué et al, 2011; Ravier et al., 2018; Salembier et al., 2021
Implementation of the design workshop	Use intermediate objects (previously made exploration tree; disruptive prototype, etc.)	3.2.3	AUTO'N, CONSYST, LEGITIMES, SDCI, SIC, SYSCLIM, VIVLEBIO, APPI-N, CASABIO, DST-WORK	Reau et al., 2012; Gillier et al, 2010
	Facilitate the exploration of new properties: stating a property contrary to that usually known; formulating the properties that characterize a known solution; temporarily playing with the constraints.	3.2.4	AGROSEM, LEGITIMES, SDCI, VIVLEBIO, APPI-N, CASABIO	Agogué et al., 2014; Brun, 2019
	Stimulate creativity, by making explicit, for each proposed option, the underlying knowledge, and encourage new explorations based on this knowledge.	3.2.4	AGROSEM, AUTO'N, CONSYST, LEGITIMES VIVLEBIO, APPI-N, CAPS, CASABIO, DST-WORK	Hatchuel et al., 2011; Agogué et al., 2014; Brun, 2019
	Entrust the design targeting a central farmer to his peers	3.2.4	AUTO'N	Guillier et al., 2020

3.3. *Outputs and outcomes of the design workshop*

On the whole, the design workshops achieved their targets (Table 4). Moreover, in most case studies, the facilitators mentioned results that had not been targeted at the outset: the workshops made it possible to convince and mobilize actors who were initially reluctant to commit to changing their agricultural practices (VIVLEBIO, SYSCLIM, LEGITIMES, DST-WORK case studies); they promoted the learning of new technical levers, unknown to some participants (all case studies); for some participants, they contributed to learning new ways of reasoning the management of their cropping systems; they were useful in prioritizing the knowledge to be produced to pursue the design or in producing new knowledge (all case studies).

Events subsequent to the design workshops differed from one case to another. In most case studies, after the design workshops, the participants formatted and shared the prototypes designed, and/or the knowledge introduced during the workshop. Indeed, during the workshops, the short duration of the discussions, and the lack of time to formalize the exploratory paths, had rarely allowed for a precise description and formalization of the designed solutions. The case managers thus organized to report to all participants on the richness of the content, in terms both of designed solutions, and of shared knowledge. In the workshops organized to design a cropping system for a 'central' farmer, the precise description of the designed system was finalized during a further meeting between the workshop facilitator and the farmer concerned.
Finally, in most case studies, an *in situ* test of the designed CS prototypes was implemented, either in an experimental station (SIC and AGROSEM case studies), or directly in the farmers' fields (AUTO'N case study). The DSTs (APPI-N, and CAPS case studies) were tested by their users, under real conditions of use, with the aim of both adapting the tool to various situations of use, and encouraging the users to learn from a new tool becoming available.

4. Discussion

Design workshops are a key approach to support innovative design in agriculture. In the 12 cases we studied, as already shown in the industrial (Elmquist and Segrestin, 2009) and agricultural (Berthet et al., 2015) fields, such an approach has shown its effectiveness to initiate a dynamic of change, to open up the range of innovations explored, and to propose new solutions that meet ambitious objectives. We propose here to discuss methodological lessons for the organization and implementation of future workshops (4.1.), and issues related to the implementation of design workshops within innovation processes in agriculture (4.2.).

4.1. Methodological lessons to organize design workshops

The results of this study substantiate and enrich the literature on methods to organize design workshops. Main lessons concern preparation, implementation, and follow-up of the design workshops (Table 6).

We highlight key elements to be considered, in the context of agriculture, to formulate a design target that is both ambitious and realistic. We observed that starting a workshop with the precise and complete definition of a framework of objectives and constraints, as previously proposed in prototyping workshops in agronomy (Vereijken, 1997; Lançon et al., 2007), tends to keep participants in their known field, and seems less generative than the partial definition of a design target, formulated by an undecidable (neither true nor false) proposal (i.e. a desirable unknown). Bos et al. (2009) likewise proposed that each of the actors involved in the design process define their *"brief of requirements"*, to integrate their expectations as a whole, instead of building a consensus, weighting the pros and cons of their different interests. Such a plurality of expectations seems to be more favorable than trade-offs for the adhesion of the collective of actors, as shown by Ravier et al. (2015), and for a broad exploration. The role of constraints in exploration is ambivalent (Hatchuel and Klasing Chen, 2017): taking them into account may either contribute to fixation effects (e.g. stickiness to the problematic situation) or, on the contrary, constitute affordance to stimulate exploration. Based on the experience acquired from the 12 case studies, it seems that the constraints that participants experience on a daily basis fix their points of view, while unusual constraints help to encourage the exploration of disruptive proposals.

The choice of actors participating in the design workshops, rarely addressed in the literature on the subject (see, for example, Vereijken, 1997; Lançon et al., 2007; Elmquist and Segrestin, 2009), was identified as a crucial step in the preparation of the workshops in the 12 case studies. Whereas the presence of participants with the same job may facilitate the discussions, encouraging a diversity of points of view and knowledge has proved to stimulate exploration (Vourc'h et al., 2018). Moreover, in the design workshops that we analysed, a primary place was given to the future users of the designed solutions, as proposed by Bos et al. (2009) and Cerf et al. (2012). They were generally involved in the three following stages: the definition of the design target, the exploration of solutions, and the definition of the evaluation criteria of the designed object. In all cases, as a basis on which to argue the choice of participants, it seemed essential to clearly identify their role, their position in relation to the ‘dominant’ sociotechnical regime and possible lock-ins (Rip and Kemp, 1998), and their ability to listen to others and interact on their proposals. Bos et al. (2009) insist on the importance of inviting to the design process all the actors concerned by the problem to be solved: for example, for livestock buildings, "*users, stakeholders, employees, and other participating beings like animals*". We show that involving pioneering actors who have already imagined and implemented innovative practices can help the collective to better share not only the challenge and the target, but also the feasibility of innovative solutions, and can therefore help to motivate actors who were *a priori* reluctant. The particular attention paid by the facilitators to the choice of participants in the design workshops is therefore, if not specific to agricultural issues, at least particularly difficult, as numerous actors can legitimately take part in design, from farmers to advisors, agribusiness firms, consumers, NGOs, local authorities, etc (Prost et al., 2017). Knowing the functioning of agricultural innovation networks (Davies et al., 2018; Kilelu et al., 2011; Klerkx et al., 2012), and the key role of innovation brokers (Klerkx and Aarts, 2013) or network managers (Berthet and Hickey, 2018) can be a valuable resource for selecting the participants of a design workshop.

The main methods used in our case studies to overpass fixation effects and stimulate creativity had already been described in previous papers, as shown in Table 5. The contribution of this article is to wrap up all these ways, and to illustrate them by examples from the agronomic field. For instance, like the KCP workshops (Elmquist and Segrestin, 2009), our case studies show the importance of sharing, within the collective of participants, a common desirable unknown that is ambitious, prospective – but realistic – and stimulating, and the usefulness of an initial phase of sharing disruptive knowledge to start the exploration.

The sequencing of the design workshops appeared to be closely linked to the choice of the target, the diversity of actors chosen to participate, and the time available, so as to maintain a balance between the broad exploratory and the in-depth phases. Facilitating a design workshop cannot be decreed: efficient facilitators are flexible, have interpersonal skills, are open to original - sometimes destabilizing - proposals, and know how to manage their own fixations, and to take up to proposals that allow the discussion to continue. Therefore, beyond the principles formulated here, which have emerged from the experiences of the facilitators, it seems beneficial to promote learning - through practice - of the know-how for design workshop facilitation, for example by setting up pairs of facilitators, involving an experienced one and a trainee.

An important feature of the objects designed in agronomy is their systemic nature, including the interactions between environmental and socio-technical conditions, and technical actions (Sebillotte, 1974; Rossing et al., 2021). In the design workshops studied, the sequencing of the meetings, and the splitting of complex objects into sub-systems, appeared as a means of organizing design efficiently, without losing sight of the whole system. This splitting of complex objects into subsystems can be compared to the division of a design process into successive design sequences, in which the design efforts (e.g. production of knowledge, exploration of properties) are successively focused on parts, easier to manipulate, of the global solution under design, leading to exploration within differentiated, and more restricted design spaces (Hatchuel et al., 2006). There is no *a priori* rule for a ‘good split’, even if a breakdown by biophysical process (water supply, nitrogen supply, weed control, etc.) is usually not optimal because these processes strongly interact within an agroecosystem. But the systemic coherence of the object finally designed is achieved only if the facilitator has been able to organize constant dialogue between the successively designed partial solutions. Intermediate objects, especially those contributing to the visualization of the solution under design, appeared to be effective means of managing interactions during the design process (Jeantet, 1998). Vinck (2009) and Klerkx et al. (2012) argue that these intermediate (or boundary) objects contribute to the representation and translation of the knowledge, practices and activities of heterogeneous actors. They give access to a part of the distributed socio-cognitive processes of the design activity, and participate in the construction of shared knowledge between actors. They contribute to shifting the actors' points of view, thus challenging them, and constitute traces of the emergence of the solution, and of the progressive construction of the problem and its solution.

Our results confirm that workshop facilitation is crucial to their success. It first consists in managing the progress stages of collective design thinking. It also aims to encourage participants, as Hatchuel and Weil (2009) pointed out in their C-K design theory, to avoid fixation effects and to make explicit the knowledge on which their ideas are based. The ongoing formalization of this reasoning (most often oral in the design workshops, but sometimes with the help of intermediate objects) facilitates the continuation of the design process, and the positioning of participants within the virtual design space. However, some participants, unfamiliar with conceptualization, may find it difficult to verbally express, in a room, their explorations and assessment of the designed solutions. Therefore, other approaches for participatory design, based on building innovations on the course of action, in platforms or in situ, such as Binder and Brandt's design:lab (2008), step-by-step design (Meynard et al., 2012), or Farmer Field Schools (Bakker et al., 2021), are better suited than design in workshops.

We show that the assessment of a design workshop, to shed light on its performance, is twofold. First, it concerns the design process from their organizers' points of view. In that aim, Le Masson et al. (2010) proposed four criteria for evaluating an innovative design process (V2OR evaluation method): Variety of solutions; creation of new Values; Originality of the solutions designed and the knowledge produced; Robustness of the solutions with respect to a change of context. Concerning "variety", we have shown that the balance between a diversified and an in-depth exploration of solutions can be very variable, and depends both on the time available and on the operational nature of the targeted outputs. Besides, reducing the range of concepts explored did not limit their disruptiveness (see, for example, Ravier et al., 2018). Second, assessment can also be performed from the participants' points of view: for instance, their learnings (e.g. appropriation of disruptive technical ideas, discovery of new ways of acting, knowledge on agronomic processes), new will to "start a concrete change in their practice" or to experiment an innovative idea. This article analysed the design workshop process from the case managers' points of view, and further studies could enrich this analysis focusing on the participants' perspective.

The methodological lessons drawn from the study are summarized in Table 6, with the intent of making them operational in the form of recommendations and points of vigilance for future design workshop organizers.

Table 6: Methodological lessons, and points to watch out in the preparation, implementation and follow-up of design workshops

Steps		**Lessons**	**Warning points**
Preparation	**Formulation of the design target**	The target clarifies the design objective; it is usually formulated to be ambitious, challenging and prospective.	It is essential that all participants share the proposed target.
	Choice of the participants	The choice of participants is decisive for the success of the workshop. Favour open-minded participants with diversified knowledge.	Hierarchical relationships between participants, or top-down postures inherited from the linear R&D model, are generally not conducive to the exploration of novel solutions.

	Choice of knowledge to be initially shared	The challenge of initial knowledge sharing is twofold: to share the same vocabulary, and a common knowledge base between participants, intended to stimulate exploration.	The objective of knowledge sharing must be clear to participants. Trying to exhaustively inventory the existing solutions to meet the target may increase fixation effects.
	Sequencing of the meetings	The design workshop can be made up of several meetings, making it possible to successively explore different contexts, or to offer a time for knowledge production between two meetings.	Meetings too far apart in time can demotivate, with the risk of losing participants in the process.
Implementation	**Broad exploration vs deepening of some paths**	The exploration phase aims to identify a diversity of solutions, disruptive compared to what already exists, or to refine a small number of ideas to produce an operational prototype in a short lapse of time.	The balance between diversity of ideas and refinement of some of them is managed according to the objective of the design workshop and is decided during the preparation phase.
	Design of systemic objects	Splitting complex objects into subsystems is a way of simplifying design without losing sight of the systemic aspect.	The systemic coherence of the finally designed object is achieved only if the facilitator organizes constant dialogue between the successively designed subsystems.
	Intermediate objects	Intermediate objects are facilitation tools that help to organize discussions, enhance direct interactions between participants, enable everyone to get involved, capitalize on, combine and assess ideas, and make it easier to grasp the systemic dimension of the artefact.	The mobilization of intermediate objects is thought out during the preparation of the design workshops.
	Facilitation	Facilitation consists in challenging the participants, guiding them in exploring and/or deepening the ideas suggested, and maintaining the collective dynamics with benevolence.	The success of a design workshop largely depends on its facilitation. The design workshop can begin by sharing rules for the collective work: listening, benevolence, openness, respect.
The design workshop follow-up		Capitalizing on what has been produced and on the knowledge gaps identified makes it possible to value and continue the work beyond the design workshop, and to possibly reconsider the choices, in the event of unsatisfactory evaluation of the prototype.	The prototype can be finalised in a smaller committee, after the design workshop, before testing it with various potential users. It is essential to inform all the participants of the outputs and outcomes of the design workshop.

4.2. *Design workshops within innovation processes in agriculture*

Design workshops are an approach used to foster innovation processes. We propose to discuss here three issues related to their use in agronomy and agriculture.

Design workshops are only one approach, among many others, used during innovation processes in agriculture. Our results show the importance of considering the relations between these different approaches to manage their interactions. First, during the preparation of design workshops, an agronomic diagnosis (Doré et al., 1997) and a diagnosis of uses (Cerf et al., 2012) could be used to define the exploration targets, as well as the initial evaluation criteria of the process, by specifying the components of the system to be modified, the desired performances, and the concepts used to initiate the exploration. Second, as shown by Salembier et al. (2021) and Verret et al. (2020), the farmer innovation tracking approach could help to formulate ambitious targets and stimulate exploration, and to open up the field of exploration with realistic concepts, thus fostering confidence in the desirable unknown, sometimes considered by the participants of a design workshop to be risky or inaccessible. Third, the assessment of the solutions derived from the workshops could contribute to inform the exploration dynamics, as shown in some case studies and by Martin (2015). The confrontation of the virtual solution with the real growing conditions (e.g. within on-farm experiments) makes it possible to evaluate the achievement of the design target, and the feasibility of implementation, and thus to enhance learning about how to stimulate a later design phase (Meynard et al., 2012). These examples stress the importance of developing research on the complementarities between design workshops and other approaches in agronomy, and on conditions for their successful articulations to foster innovation processes, and especially open innovation processes (Chesbrough and Bogers, 2014).

To support innovation processes, some issues require that agricultural techniques be managed at the landscape level, and to consider other scales and actors than those involved in the management of cropping systems or decision-support tools. Thus, controlling the spread of a disease or a pest in a landscape, by organizing mosaics of cropping systems (Skelsey et al., 2010), managing cropping systems within a water catchment area to improve water quality (Chantre et al., 2016), or introducing a diversifying crop in the cropping systems of a territory (Leclère et al., 2018; Hufnagel et al., 2020) require not only the design of cropping systems, but also of their spatial organization, their link to the actors of the territory, and their coupling with other innovations, whether technical or organizational (Meynard et al., 2017). Design workshops to rethink territories have already been organized with such objectives (Berthet et al., 2016; Della Rossa et al., 2022; Pelzer et al., 2020). Such a design can benefit from a prior analysis of the obstacles to the development of certain innovations, linked to the system of actors involved: a diagnosis of the sociotechnical system can be mobilized in this sense (Meynard et al., 2018; Della Rossa et al., 2022). An analysis similar to the one presented in this paper, conducted on workshops organized to design territories, would make it possible to identify the particularities and common elements of such workshops.

In all design workshops analysed, a wide diversity of knowledge was mobilized: knowledge from the experience of certain actors *vs.* scientific knowledge; knowledge on the issues or processes at work in agroecosystems *vs*. knowledge on the production context; and generic knowledge *vs.* knowledge on singular situations. This confirms the need to combine a wide variety of complementary types of knowledge for innovative design in agriculture (Doré et al., 2011; Ernesto Méndez et al., 2013; Geertsema et al., 2016). Innovation processes in agriculture thus increasingly respond to open innovation logics (Chesbrough and Bogers, 2014; Prost et al., 2017), where the knowledge mobilized for the design of agroecological solutions is widely distributed among stakeholders, and the design process involves a diversity of actors, belonging to different firms. As shown in the design workshops studied, the objects to be designed in agriculture are subject to strong uncertainties, linked to the unpredictability of biological processes, faced with the variability of the environmental factors influencing them (Brugnach et al., 2008; Prost et al., 2017), and to gaps in the knowledge necessary for their design, particularly concerning the biological regulations within the agroecosystem. One of the roles of the design workshops is thus to point out knowledge gaps that need to be filled as a priority (e.g. between workshop meetings), over those that, while generating uncertainty, do not block the design process (Leclère et al., 2018; Toffolini et al., 2020).

5. Conclusion

Based on a collective cross-analysis of 12 case studies of workshops managed to design new cropping systems or decision-support tools, and on the principles of the C-K theory of innovative design, we derived methodological lessons on the collective design of systemic objects in agriculture. The analysis shows convergences with design workshops carried out and analysed by other authors in other fields, as well as particularities linked to the specific features of design in agriculture: the importance of the choice of participants; the management of the systemic nature of the designed objects; or the mobilization of intermediate objects intended both for the shaping of the new product and the organization of the coordination between its designers. Finally, we confirm that conducting a design workshop cannot be improvised: it is based on a rigorous preparation and a know-how of facilitation, which cannot be reduced to few "tricks".

However, this cross-cutting analysis of the management of design workshops dedicated to agriculture remains focused on the design of cropping systems and decision-support tools. It would be interesting to enrich the approach through the analysis of workshops dedicated to the design of farming systems, landscapes or coupled innovations aimed at supporting the transition of food systems. It would then be necessary to enrich or revise certain organizational principles, as well as the management of complementarities with other methods, such as those helping to define design targets and participants, or organizing the confrontation of designed prototypes with reality. Research on workshop-based design, which makes it possible to manage the diversity of the different actors' expectations and constraints, is only in its infancy. Finally, our research has shown that design workshops promote collective design in agriculture, and feed open innovation processes.

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Supplementary material: a detailed presentation of the 12 case studies

1. AGROSEM: Designing pesticide-free seed-oriented CSs, for their experimental assessment (2018)

The project AGROSEM, initiated by the FNAMS (national federation of seed multiplier farmers), aimed at producing healthy and pure seeds without pesticides. The objects designed were CSs including a crop sequence of 5 to 6 crops, all intended for seed production, and their crop management system, as well as the protocols to experiment with them for 8 years on 3 sites. The design workshop was held over 3 days, gradually complexifying the targets by going back and forth between crop management and crop sequences. During the workshop, a decisional diagram representing the crop sequences with the key interventions was used as a support for facilitation to visualize the interactions between technical choices, and was spontaneously remobilized by the experimenters to build the protocols during the third meeting. The designed CSs are currently being tested in experimental field conditions.

2. AUTO’N: Designing arable nitrogen-autonomous CSs, with and for farmers (2016-2017)

The aim of the AUTO’N project was to design N-autonomous CSs with a group of 7 farmers in the north of France. Seven meetings were organized, each one around the specific target of a 'central' farmer, corresponding to the results he expected and his specific agricultural situation (Guillier et al., 2020). Expectations regarding nitrogen varied among the 7 farmers: ensuring sufficient N nutrition for crops, increasing C and N storage in the soil to mitigate global warming, or lowering N losses into the environment to contribute to improving water and air quality. During each meeting, the farmer explained his expected results and constraints, after which his peers built solutions (several SCs) to address them. A board game (‘Mission Ecophyt'eau’) was used to facilitate exchanges and trace proposals, and assessment tools were employed to validate the *a priori* capacity of the proposed solutions to obtain the results expected by the ‘central’ farmer. Then, on the basis of the proposals, the ‘central’ farmer chose those he wished to test on a part of his farm.

3. CONSYST: Designing arable CSs including crops to feed a biorefinery (2017-2018)

The CONSYST project aimed at co-designing CSs including crops for a biorefinery in the north of France. Two one-day meetings were organized to design the CSs for two major soil types within the territory. The target was defined during a preparatory meeting between the project managers. Three strategies to reach the target emerged from the first day: increasing the number of crops per year; crop specialization (biomass *vs.* food production); and diversification in biomass uses. The CSs designed for each soil type were then assessed with the STICS crop model (Ferchaud et al., 2020) and with a

Life Cycle Assessment (LCA) tool. During the design workshop, a calculator (specifically created for this workshop) and knowledge sheets facilitated the exploration, and enabled choices to be made among the alternatives proposed by the participants.

4. LEGITIMES: Designing CSs including more legume crops within three territories (2015)

The LEGITIMES project aimed at studying and co-building the conditions for inserting more legume crops into the cropping systems of three French territories: Pays-de-Loire, Midi-Pyrénées and Burgundy. A one-day meeting per region was organized to design CSs including legume crops, generally starting from existing CSs. Three to six CSs were designed per region (15 CSs in total), in Organic Farming and conventional agriculture, for cereal growers and farmers in mixed crop-livestock farming. A multi-criteria assessment of the designed and existing CSs allowed the case managers to identify the most promising ones to be disseminated, or to use some of them to design territorial scenarios for the development of legume crops (Pelzer et al., 2020).

5. SDCI: Designing pesticide-free CSs, for their experimental assessment (2006-2012)

In 2006, with the aim of promoting a more sustainable agriculture, a group of actors from R&D in agriculture (from the mixed technology network "Innovative Cropping Systems") wished to design and experiment innovative cropping systems (Reau et al., 2012). Several meetings, bringing together researchers, engineers and advisors, were organized to design these CS based on the diagnosis and improvement of the current ones. The objects designed were pesticide-free CSs, adapted to a region. The objectives were softened over the course of the meetings to prepare and allow for their experimentation. The exploration was based on functional diagrams of the expected services, and tables of practices contributing to these services. These CSs were then experimented within several dozens of fields.

6. SIC: Designing arable CSs limiting GHG emissions, for their experimental assessment (2014-2015)

A previous experimental study of CSs designed by experts for very ambitious objectives (simultaneous reduction of GHG emissions and pesticide use) showed that these tested CSs did not achieve the expected results (Colnenne-David et al., 2017). To increase the chances of achieving these ambitious objectives, a two half-day design workshop was organized, bringing together researchers with different skills and agricultural advisors. The design workshop began with a tour of the field dedicated to the testing of the first prototypes and a presentation of their results. Then, divided into two groups (with or without soil tillage), the participants designed several new CS prototypes. As the *ex ante* assessment of their performance was unsatisfactory, a new design meeting attended by field researchers and agronomists led to new CSs prototypes. Their *ex ante* assessment was more satisfactory, thus leading to the selection of the most promising CSs prototypes, on which the long-term experimentation have been running since 2015.

7. SYSCLIM: Designing arable CSs with low GHG emissions, within a collecting area (2013-2015)

The objective of the SYSCLIM project was to design, with a cooperative in eastern France, alternative CSs achieving lower GHG emissions, and adapted to the local agricultural context (Angevin et al., 2016). As the territory was characterized by two contrasting pedoclimatic zones, a design meeting per zone was organized, each lasting one day. The farmers' concerns regarding their current CSs were used as a starting point to develop evaluation criteria and proposals for alternative crop techniques. The two meetings produced two different results: very positive feedback on the CSs designed, in one, but a lack of adherence to the approach in the other. The CSs designed were evaluated using a multi-criteria tool, and were then presented to different scientific and technical audiences.

8. VIVLEBIO: Designing innovative strategies to manage perennial weeds (thistle) in Organic Farming (2018)

The objective of the VIVLEBIO project, led by the R&D Agrotransfert-Ressources-et-Territoires organization (in northern France), was to help farmers to design multi-annual strategies for the management of thistle in Organic Farming (OF). The purpose of the workshop described here was to design a set of strategies to "live with thistle in OF". This proposal was derived from on-farm innovation tracking (Salembier, 2019) which had shown that some farmers consider thistle as a provider of services and not only as a pest. The aim was to explore systemic combinations of crop techniques, that should be further refined in specific situations. This was done based on individual proposals written on sticky notes. The design workshop helped to define original strategies for the management of these perennial weeds in OF, and to stimulate the interest of participating farmers to get involved in the project (through their commitment to experimentation, or to be engaged in writing a knowledge sharing blog).

9. APPI-N: Designing a Decision Support Tool (DST) to manage wheat N fertilization while tolerating N deficiencies (2014-2015)

The objective of this workshop was to design a nitrogen fertilization method for winter wheat that would address the issues identified by the users of the balance-sheet method, widely recommended and used until now in France (Ravier et al., 2018). The designed object is a DST, based on the monitoring of the N nutrition index (i.e. a NNI trajectory) of the crop to be fertilized, in order to decide the date and dose of N fertilization. The first meeting, lasting one day, started with a presentation of the analysed difficulties of using the balance-sheet method. Sharing these issues helped to orient the exploration towards a method without a yield target and without measuring soil mineral nitrogen content (two key variables for the balance-sheet method), with the agreement of the participants on this new design target. A second day, one year later, started with the presentation of a first prototype of the DST under design, which allowed the participants to refine its properties. Currently, farmers are cooperating in testing and enriching an operational prototype of the DST.

10. CAPS: Designing a DST to help choosing the companion species to grow with rapeseed, according to the ecosystemic services targeted (2015-2016)

The objective was to design a tool to help in selecting companion species to be associated with oilseed rape, taking into account farmers' expectations and their agricultural situation, and mobilizing the trait-function-service conceptual framework (Violle et al., 2007). The design was carried out over two successive collective meetings: during the first one, the target of the design and the approach mobilized were defined, while the second started with discussions on the structure of the tool and the knowledge to be included in it. Using a generic table presenting the links between traits, functions and services, built up from the bibliography, the facilitators organized a knowledge exploration to complete the table. The CAPS tool is now operational and available online (https://www6.versailles-grignon.inrae.fr/agronomie/Productions/Outils-et-modeles/Caps-Colza-associe).

11. CASABIO: Designing rules to mix wheat cultivars in Organic Farming (2018)

The role of wheat variety mixtures in reducing diseases is well-known (Finckh et al., 2000). The CASABIO project aimed to design rules for composing wheat variety mixtures, based on agronomic and genetic levers, to manage not only diseases but also weeds and nitrogen nutrition in Organic Farming. Two thematic meetings, respectively focused on weeds and nitrogen management, were organized, each exploring agronomic and genetic strategies and levers. They were based on two knowledge exploration trees, previously built by the facilitators and then enriched during the meetings. The design workshop thus produced a synthesis of knowledge finalized by the design of variety mixtures, but which will need to be reworked to come up with generic rules for variety mixtures.

12. DST-WORK: Designing a DST to take into account work in the change of practices (2017)

This project was based on the finding that there is a lack of tools to help farmers to take into account the work (in terms of time and organization) involved in changing practices towards a more sustainable agriculture. The objective was therefore to design tools to support farmers before or during the testing of new techniques. Two one-day meetings were organized, the first with farmers and the second with specialized advisors. After sharing the results of a diagnosis on existing tools and farmers' needs (Delecourt et al., 2019), a broad exploration led to the design of a tool kit covering numerous dimensions of their work. At the end of the workshops, 30 complementary concepts of DST were proposed. These concepts are now to be transformed into operational prototypes, which will be tested in real conditions.