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RESEARCH ARTICLE

Analyzing co-design of agroecology-oriented cropping systems: lessons to build design-support tools

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Abstract

If the challenges involved in agroecological transition are to be addressed, cropping systems (CS) need to be changed profoundly, which in turn requires innovative design adapted to local conditions. This is however by no means an easy task since such design activity requires extensive knowledge on objects and processes rarely studied until now, most of which is distributed among numerous stakeholders. Since the 2000s, research on design in agriculture has aimed at developing participatory methods to support on-farm design of new systems, but few studies have focused on the elaboration of design-support tools. With a view to defining the features of tools intended to support the design of agroecology-oriented cropping systems, ergonomists recommended an analysis of the activities of the future users of these tools in their real work situations. We started out by implementing a diagnosis of use situations, based on observations of real collective design activities. To this end, we took part in six design workshops, which differed in terms of goals and of designers participating (i.e., farmers, advisors, students, or scientists). We first identified the diversity of features of these design situations, and then analyzed three processes across the design workshops: (i) the reformulation of the design goal; (ii) the large exploration of candidate solutions; and (iii) the local adaptation of these solutions while anticipating the on-field implementation. Here, we show, for the first time, the type of reasonings and knowledge that designers and facilitators displayed and used throughout the agroecological cropping system design process. We identify the features that future design-support tools should have to guide co-designers of agroecological CS. Such tools should promote several types of design reasoning and allow the development of external representations of the object under design. Our results provide operational guidelines for the elaboration of new design-support tools.

Keywords Use situation · Design process · Design workshop · Agroecology · Distributed knowledge · Design reasoning

1 Introduction

To support agroecological transition, cropping systems (CS) need to be changed profoundly, which in turn requires disruptive innovations (Meynard et al. 2012; Berthet et al. 2019). Adherence to the key principles of agroecology (Altieri 2002) requires CS to be less dependent on external synthetic inputs, and to rely on ecological and natural processes such as nutrient cycling and biological pest regulation. These processes make agroecological CS highly dependent on interactions among techniques and on interactions between techniques and environment (Meynard et al. 2012; Toffolini et al. 2017). Such CS are site-specific because (a) they target a set of objectives which may vary from case to case, depending on the farmer's means and values; and (b) they are designed to fit the highly variable constraints and opportunities of local situations in terms of climate, soil, landscape, environmental susceptibilities, and socio-economic conditions (Prost et al. 2017). It follows that agroecological CS cannot easily be designed, as this variability makes outcomes in the soil-crop system difficult to predict. This, in turn, hampers the direct dissemination of standardized alternatives among farmers (Meynard et al. 2012).

Design theories have shown that design processes are largely informed by knowledge (Visser 2006; Hatchuel and Weil 2009). Recent research studies have provided advances on the use of heterogeneous forms of knowledge to design

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agroecological CS, including both experience-based and science-based knowledge (Coolsaet 2016; Prost et al. 2017; Girard and Magda 2020). Some authors underline the value of experience-based knowledge, often produced in the action (Schön 1992; Prost et al. 2018), as a way to fill some of the numerous gaps in the scientific-based knowledge, including fundamental knowledge. Fundamental knowledge is defined as generic knowledge on key biological or physical processes (e.g., knowledge on symbiotic fixation) or objects, generally produced in scientific experiments, with controlled protocols and statistics-based results (Caron et al. 2014; Toffolini et al. 2017). Such experience-based and situated knowledge needs to be decontextualized, that is, reformulated to produce generic knowledge, before being used in new situations (Toffolini et al. 2017; Girard and Magda 2020). These large amounts of knowledge, which are useful to design new agroecology-oriented practices, are distributed among numerous actors (Girard and Magda 2020). Sharing this knowledge in a distributed Agricultural Knowledge and Information System is in fact a condition if the overall design capacity in agriculture is to be increased (Klerkx et al. 2012). It thus seems necessary to improve access to situated and generic knowledge, and its sharing among stakeholders, and to favor the hybridization between experience-based and science-based knowledge, in order to inform design processes that support agroecological transition.

Design processes involve three main cognitive activities, which are not sequentially organized but are largely interdependent (Darses et al. 2004; Visser 2009): redefinition of the design problem (hereafter design goal); generation of solutions; and evaluation of solutions. As design problems are often large and complex, as in the case of agroecological transition, they often require the articulation of multiple skills, which fosters collaboration between co-designers from various disciplines or professions (Détienne 2006). To support collaborative design between stakeholders (farmers included), design-support oriented methods have been developed in the last decades (Le Gal et al. 2011; Meynard et al. 2012; Martin et al. 2018). In the agroecological transition, farmers have been identified as designers of their own system, whereas they were formerly mostly technology adopters while implementing input-based systems (Salembier et al. 2018; Lacombe et al. 2018). For example, design workshops were proposed to bring together farmers and other designers (such as advisors and researchers), to share knowledge and ultimately to support co-designing of cropping systems with ambitious new aims (Bos et al. 2009; Berthet et al. 2016). Moreover, numerous tools have been developed in the last decades in agronomy to support the change of practices. While decision-support tools guide farmers to take more effective decisions (Rose et al. 2016), for instance to select one solution among a range of existing ones, design-support tools facilitate the invention of solutions that do not yet exist (Hatchuel 2001). They have been described either as being specific to one design goal (e.g., the change of practices in catchment areas to improve water quality, in Prost et al. (2018)), or as focusing on the design of one type of object (e.g., livestock systems in Martin et al. (2018)), or as supporting the *ex ante* evaluation of solutions (Colnenne-David and Doré 2015), as one step of the design process. They rarely aim at sharing a large amount of knowledge on a diversity of agricultural systems and covering various subjects (e.g., reduction of pesticide use, N autonomy, biological regulation, soil fertility, etc.). Considering the diversity of design situations (e.g., objects being designed, design goals), there is thus a real challenge to develop generic tools to support the generation of solutions within the agroecological CS design process, that is, solutions that draw on the knowledge distributed among numerous stakeholders and support the invention of disruptive solutions rather than the selection among already known alternatives. We define design-support tools as external support (either physical or digital), such as games (Speelman et al. 2014), sketches, figures or diagrams, and their underlined methods, that feed the design activity. Sketches for instance support the exploration of solutions (Brun et al. 2016). Design-support tool also allow the construction of external representations of the object under design to support complex design processes (Visser 2006; Détienne 2006; Safin et al. 2012) and thus the dialogue between designers and theses external representations (Schön 1983). Last but not least, such tools support dialogue between designers, as boundary objects, and thus sustain the establishment of common ground (Boujut and Blanco 2003).

In the study reported here, we explored the following question: what are the desired features that future design-support tools should have to support designers of agroecological CS? We performed a diagnosis of use situations based on in-situ observations to analyze design processes during the course of several design workshops (Fig. 1). The result section outlines the commonalities and differences among design situations and among design processes, and proposes guidelines for future design-support tools. We finally discussed our main findings.

2 Material and methods

2.1 General method and description of case studies

The involvement of future users throughout the design of a new tool helps to ensure that the diversity of users' activities and the various situations in which the tool will be used, are taken into account (Béguin 2003). To do so, ergonomists recommend a method to analyze the activity of the future users of the tool in their real work situation: the diagnosis of use situations (Cerf et al. 2012). This method has already been successively implemented by several agronomists, even with a

Fig. 1 Design workshop that brought together farmers, advisers and scientists to co-design organic crop management of rapeseed for two farmers of the group.

tool that is not yet in use (Lecomte et al. 2010; Cerf et al. 2012; Ravier et al. 2018; Delecourt et al. 2019). It thus helps to identify features and affordances of the tool under design, to match its future uses (Ditzler et al. 2018). For the first time, we implemented a diagnosis of use situations based on in-situ observations. We took part in six case studies in France, in which agroecological cropping systems were co-designed. Design workshops in the case studies consisted of one or more steps (Table 1) proposed by Berthet et al. (2016) and Reau et al. (2012). According to these authors, an entire design workshop is composed of consecutive steps: (i) the definition of the design goal (also referred to in the literature as design target); (ii) a step which aims at sharing some knowledge chosen to be a first common basis among participants (e.g., expert presentation of ecological process), serving to foster the subsequent exploration process; (iii) an exploration phase resulting in the identification of disruptive techniques, without considering their link with the precise context; and (iv) the construction of solutions (here cropping systems), through their refinement, to build a consistent system tailored to the context. In every workshop, a facilitator prepared the overall organization and managed the interactions among participants during the design process (Table 1).

The data collection took place between December 2018 and March 2019. Discussions were recorded and transcribed—when authorized (from D1 to D4)—observations were made and pictures taken of the use of existing tools. Our six case studies (Table 1) differed in terms of the goal, the designers participating (i.e., farmers, advisors, and/or students, and/or scientists, and/or the leader of a system experiment), the objects to be designed (cropping system or crop management plan), and the type of agricultural system considered (organic or conventional).

2.2 Data analysis

Since all cases occurred in collective design workshops (characterized by a short-term collective design activity), we first classified the design situations according to four criteria, based on the definition in cognitive ergonomics (Visser 2009): (i) the diversity and features of the design goals; (ii) the traits of the designed objects; (iii) the diversity of designers and their expertise in the domain concerning the workshop (their knowledge and experience on the subject), and the roles of the facilitators; and (iv) the tools used to support the process during the workshops, and their uses (Fig. 2). Second, we analyzed the commonalities and differences among processes occurring during design workshops: the reformulation of the design goal, the exploration of solutions, and the local adaptation of solutions for the preparation of their implementation (Fig. 2).

We conducted a cross-analysis to understand how designers used knowledge to generate solutions during the workshops, and to anticipate the on-farm implementation of these solutions. To do so, we described the reasoning adopted by designers to explore a diversity of new solutions while building an agricultural disruptive system able to reach the ambitious goal defined at the beginning. In particular, we identified the types of knowledge that had been shared during interactions, and how each type was used to progressively shape the artifact. We then analyzed the way designers used existing tools or other resources, either human or material, and how they fitted these tools into their design process to manage their cognitive and organizational activities. Finally, based on the literature and on our cross-analysis of case studies, we were able to derive and define features for tools to be developed to support either designers or facilitators of design workshops in the design of agroecological CS (i.e., tools to support the generation of solutions).

3 Results

3.1 Features of co-design situations

3.1.1 Diversity of design goals, designers, and designed objects among co-design situations

All design situations differed in terms of the design goals to be reached (Table 1). They were either specific, concerning only one element of the CS (e.g., manage one specific weed in D1), or much broader, related to production factors (e.g., reduce the use of pesticides in D3; cease the use of glyphosate in D4). They were sometimes expressed as the targeted performance, with the indicator being defined (e.g., CS to reach a minimum amount of nitrate leaching during autumn in D2).

Regarding the objects to be designed (Table 1), they first varied in time scale (e.g., crop management over one crop cycle in D3, or CSs over several years in D1). Moreover, their level of implementation differed from case to case: some CSs were intended to be implemented in one particular farmer's

Table 1 Characteristics of the six design workshops used as case studies.

	Design goal to be reached	Designers (facilitators are not included)	Facilitators	Location and institution	Time scale of data collection	Designed object and level of implementation targeted	Tools	Steps in the design process
D1	Manage perennial weeds without herbicide (three workshops)	Farmers and advisors, between 5 and 7 depending on the workshop	Engineer of the Agricultural Research and Developement Institute (also designers)	Hauts-de-France –Agricultural Research and Developement Institute	One half-day meeting (three times)	Organic cropping systems, with implementation	Drawing, model of the evolution of the root reserves of thistle	1, 4
D2	Reduce water pollution in a catchment	20 farmers	Advisors	Normandy - local Chamber of Agriculture	One day meeting	Conventional cropping systems, without implementation	Handmade card to design the CS	1, 3, 4
D3	Manage rapeseed without insecticide	5 farmers, 2 advisors, 1 researcher and 1 pilot experiment	Advisors (also designers)	Ile-de-France –INRAE and a local association of organic farmers	One day meeting	Crop management plans of rapeseed, with implementation	Handmade card to design the crop management plans, biology-based resources (Quinio et al. 2022), written testimony	1, 2, 3, 4
D4	Manage a glyphosate-free cropping system (herbicide)	12 farmers and 2 advisors	Advisors (also designers)	Britanny – local Chamber of Agriculture	One day meeting	Conventional cropping systems, without implementation	The board game Mission Ecophyt'Eau (de Marguerye et al. 2018)	1, 3, 4
D5	Be resilient without tillage in a catchment area	16 students in agronomy ; crop production	Teacher	Normandy - secondary school	One half-day meeting	Conventional no-till cropping systems, with implementation	No tool	1
D6	Develop mycorrhizal networks in arable cropping systems	16 students in agronomy ; crop production	Teacher	Normandy - secondary school	One half-day meeting	Mycorrhizal network within an arable cropping system, without implementation	Mymyx approach (Chave et al. 2019)	2, 3, 4

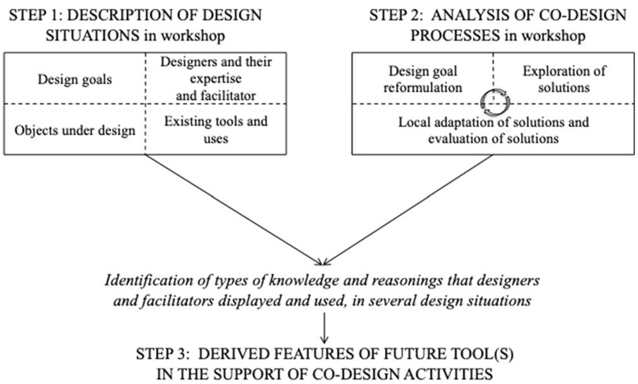

Fig. 2 Conceptual framework to identify the features of tool(s) in the support of co-design activities, based on characterization of both the design situations and three interdependent processes: the design goal reformulation, the exploration of solutions and the local adaptation of solutions.

field (situated CS in D1, D3, and D5); other designed CSs had to be relevant for a large range of conditions within the area (generic CSs designed in D2, D4, and D6). Finally, the designed cropping systems were either organic or conventional, which drastically changed the techniques and the knowledge that could be mobilized for design, and concerned various regions in France.

The designers' jobs differed between and within the studied groups (Table 1). Apart from the facilitator(s), the groups were composed either of farmers only (D2), or of farmers and advisors (D1, D4), or farmers, advisers, managers of system experiments, and scientists (D3), or only students (D5, D6). In some cases, the facilitators were also involved in the design process (D1, D3, D4). The levels of expertise—related to the design goal—that designers had before attending the workshop varied widely; they were either novices or experts in the domain concerned by the workshop. As an example, in D1, before the workshop, farmers had acquired relevant science-based knowledge on the biology of perennial weeds (e.g., dynamics of root reserves explained by a specialist in weed biology) through previous meetings dedicated to knowledge sharing. They had also learnt from their experience through their own observations in their fields (e.g., rapid regrowth of thistle after plough stubble). By contrast, in D6, students had little if any knowledge on mycorrhiza at the beginning of the design process. Finally, only a few farmers and advisors had experience in design workshops (D1 to D4) and were spontaneously inclined to explore outside of their usual practices.

3.1.2 Diversity of uses of existing tools during the design workshops

In these various co-design situations, both designers and facilitators sometimes used tools which were adapted to either specific or broad design goal. First, in all cases, designers used tools to share a common visual representation of the object being designed. Thus, game objects (e.g., cards, board, etc.) were used to visualize and manipulate the complex system under design (step 4 of design workshop). In D6, for instance, students used a board game to establish and maintain a mycorrhizal network over one crop cycle. To obtain the maximum number of filaments (represented as sticks they could manipulate), they had to select cards describing practices (each one being associated with a specific number of filaments) favoring the establishment of the mycorrhizal network (Fig. 3a—MYMYX game). Another tool, combining a game board and cards, was used in D4 to build alternative crop rotations to manage weeds (Fig. 3b—Mission Ecophyt'Eau). Farmers chose crop cards and practice cards, and then organized them on the game board to visualize the CS under design (e.g., introduction of a new crop, use of mechanical weeding). They successively selected one card (or drew a new card) and discussed the underlying new idea and its ability to improve the coherency of

Fig. 3 Use of design-support tools to visualize the object under design. Establishment of mycorrhizal network between the plant roots (at the four corners) on a board game, in order to reach the nutritive resources (colored pieces), using sticks representing mycorrhizal filaments (in white) and cards describing practices influencing the mycorrhizal network (case D6, **a**). Design of a conventional CS without glyphosate using the board game Mission Ecophyt'Eau, crop cards and practice cards (case D4, **b**).

the proposed CS. The group then approved (or rejected) the solutions identified. Such cards brought knowledge (partly unknown by the designers) that was thus shared and applied to techniques of interest for the design target.

Second, other types of tools served to enhance knowledge sharing among designers within each workshop (D6, D3, D4). For instance, facilitators used the quiz developed in the MYMYX game, to learn about and discuss the impact of farming practices on the mycorrhizal network. The quiz equipped students with new knowledge required, which was then used to design a cropping system fostering mycorrhizal networks (specific design goal in D6). The design workshop in D3 moreover provided opportunities for knowledge sharing (step 2), through the presentations: (i) by an expert, of the biological cycle of main insect pests in oilseed rape, with a view to designing low-insecticide crop management; and (ii) by an advisor, of results from an experimental station, to describe alternative techniques and the interpretation of their effect on the targeted results. Last but not least, during the exploration of solution in D4 (step 3), the facilitator of the workshop presented a successfully implemented agroecological system of a farmer in a written form (French DEPHY Network). Part of this knowledge, that participants learned, was subsequently used in the design workshop (steps 3 and 4).

Finally, facilitators sometimes relied on tools dedicated to managing the overall organization of the workshop. For instance, in D6, teachers followed the procedural plan provided in the MYMYX approach to guide students in the successive steps of their design activities, to first acquire and then apply knowledge on mycorrhiza (using a quiz performed before the design phase). The approach recommended in the Mission Ecophyt'Eau tool also guides designers in the design process (broad design goal), to first use pest cards to identify the conditions favoring or limiting pest development (step 3), and then to build the CS on the basis of this knowledge (step 4).

3.2 Features of the design process during co-design workshops

3.2.1 Designers and facilitators followed various types of reasoning to reformulate the design goal

We observed how (i) designers shared the design goal whether it was specific or broad, usually initially defined by the facilitator; and (ii) it was refined, reformulated, and thus clarified throughout the design process, so that it became a common desired goal among participants of the workshops. With this aim, we identified two types of reasoning: the decomposition of the design goal in sub-goals, or the formulation of constraints (Table 2). In D1, facilitators formulated the initial and specific design goal: the management of perennial weeds in organic systems, which was a common issue shared by the farmers attending the workshops. Throughout the design process, the "target" farmer himself redefined and reformulated the goal to specify the constraints and opportunities of his own situation (e.g., soil type, available equipment), which were then used so that the proposed solutions were consistent with this situation. In some cases, it helped co-designers to think outside the box which enabled facilitators to remove some constraints. For instance, in D2, facilitators asked farmers to design a system thinking 10 years ahead, in order to delete current socio-economic conditions unfavorable to the selection of some alternative practices (e.g., farmers discussed the advantage of introducing hemp in their CS, even if there was not yet a local market for it). Another strategy used by the facilitators when the design goal was much broader, was to define more precise sub-objectives (goal decomposition). For instance, in D2, as farmers had to build CS that reduced water pollution at the scale of a catchment area, facilitators (here advisers) defined two specific sub-objectives, concerning either nitrate leaching or pesticide pollution (Table 2). They formulated these sub-goals with indicators related to expected performances of the CS, in terms of nitrate and pesticide concentrations in the water (i.e., maximum level of nitrate leaching in autumn to achieve nitrate concentration below the legal threshold of 50 mg/l, and maximum pesticide application to reach pesticide concentration below 0.075 μg/l). The reformulation of design goals occurred in every situation, so that it became a common step for all designers (Table 2). In most cases, we observed that no tool has been used to reformulate the design goal, except in D2, facilitators identified sub-goals to build a mind-map which they shared with the entire group.

3.2.2 Exploration of solutions: Types of reasoning and mobilization of knowledge

During the exploration phase of the design process, we noted that designers considered a large number of alternative solutions (breadth-first exploration in D4) and/or developed an in-depth idea (depth-first exploration in D3), whether the goal was specific or broad. For instance, in D4, facilitators managed a breadth exploration asking each farmer to share several candidate farming techniques addressing the design goal, and the reasons of their choices (during a "post-it" session). Moreover, in all cases, we observed the following three types of reasoning (Table 3 including quotes). First, we noted that co-designers reused existing solutions to widen their search, following an analogical reasoning. These solutions were mostly practices or combinations of practices with known and explicit contributions to the design goal, as they had previously been implemented in analogous situations with a similar design goal. Such practices were either orally shared by farmers during the exploration phase of the workshop, or mentioned by one farmer, through one testimony during the knowledge sharing step at the beginning of the workshop (step 2), or shared by the facilitator or one participant, based on reports in the literature or from other farmers (not attending the workshops). For example, one experienced farmer orally described his successful management of rapeseed without

Table 2 Features of the design goals and strategies for their reformulation

	Design goals to be reached	Features of the design goal	Strategies to reformulate design goals
D1	Manage perennial weeds without herbicide	Specific goal	One farmer, attending the workshop, described the local context, its constraints and opportunities: control thistle in one of his fields, after two years of alfalfa, in a no-till system
D2	Reduce water pollution in a catchment	Broad goal with territorial issue	The facilitator removed constraints and ask farmers to design a system thinking 10 years ahead, and also identified sub-goals by formulating indicators: reach (i) nitrate concentration below the legal threshold of 50 mg/l and (ii) pesticide concentration below 0.075 μg/l
D3	Manage rapeseed without insecticide	Specific goal focusing on management of one crop	One farmer refined the design goal by specifying local context, its constraints and opportunities: he added a personal objective, his target yield: produce a minimum of 10 quintals in order to produce its own oil
D4	Manage a glyphosate-free cropping system (herbicide)	Broad goal with strong constraints from national issue	- The facilitator identified complementary sub-goals: (i) destroy the cover crop without using glyphosate, (ii) manage weeds, during the crop, without using glyphosate, (iii) destroy meadows without using glyphosate - Farmers had to define further constraints: with or without herbicides
D5	Be resilient in a catchment area	Broad goal	The farmer identified sub-goals, and added another personal objective: improve not only water quality but also soil structure (in a no-till system)
D6	Develop mycorrhizal networks	Specific goal	Students refined the design goal by specifying the local context, its constraints and opportunities: develop mycorrhizal networks within fields of wheat, onion, apple trees and beans to reach the nutritive resources

pesticide (D3), including spring pea as a previous crop, explaining that the fixed-N provided to the oilseed rape at the beginning of its cycle enhanced its growth, resulting in better pest control. Farmers at the workshop reused some of the ideas discussed, in the design process. As the spring crop was not suited to the new design situation (the local climate with drought during flowering time), they discussed the introduction of another winter or perennial legume crop before oilseed rape. Written testimonies were used by the facilitator to support analogical reasoning (farmer in D3, experimental station D4).

Second, we found that designers relied on function-based reasoning to build generic solutions. They used knowledge on biological objects or on ecological processes (e.g., biological cycle of natural enemies to control pests, biological N fixation) that either the facilitator of the workshop, an expert in a domain, or a farmer attending the workshop provided, and which included both scientific-based knowledge and experience-based knowledge (Table 3). In the exploration of solutions, designers looked into functions, defined as an effect on the biological object or processes within the system, and identified farming practices affecting these functions. They either explained the effect of a practice proposed as a solution, thus identifying its contribution to the goal, or imagined other practices affecting the same function, but that were better adapted to the situation under design. For example, in D1, to foster thistle exhaustion (function), farmers knew they had to till the soil in June while root reserves of thistle are at their lowest rate (biological knowledge), since they had learned about the dynamics of thistle root reserves during previous meetings. Therefore, during exploration, farmers either evoked known farming techniques to exhaust thistle, or devised a completely new and as yet unknown solution. To be able to plough stubble at the appropriate time, they proposed the introduction of new crops with either early harvesting (e.g., harvest of spring pea before June, Table 3) or late sowing (e.g., sowing of green beans after June). A knowledge-based tool was used by one of the experts to support the function-based reasoning: the tool linked knowledge on insect pests affecting rapeseed—that had been shown to be useful to design strategies to control such pests—with farming practices contributing to control these pests (in D3, Quinio et al. 2022).

Third, designers followed systemic reasoning to identify the generic interactions between practices required to reach a design goal. More specifically, they advocated the need to combine techniques or shed light on antagonistic effects between practices, regarding the targeted goal. For instance, in D3, one function proposed to control autumn insects in rapeseed was to strengthen the plant early in the crop cycle, through early sowing and high soil nitrogen availability at sowing. To reach these conditions, farmers discussed the introduction of winter pea as a previous crop, due to its early harvest and the release of a large amount of nitrogen from pea residues. Yet, as weed control was considered to be difficult in a winter pea crop, they built alternative solutions to address this issue: either to grow a pea-barley intercrop (more competitive against weeds), or to implement mechanical weeding. By doing so, designers adapted technical options to the whole environment (macro-climate and soil type, Table 3). In our case studies, no tool was used to promote systemic reasoning.

We also noticed that co-designers, whether novices or experts, could be set on one solution (e.g., a student stuck on one popular idea, or an advisor set on the practical solutions he/she knew). One strategy mobilized by the workshop facilitator in D3 was to ask the "target" farmer not to intervene in the exploration, to avoid fixation effects, and to give his opinion

Table 3 Knowledge types used by designers in workshops during the exploration of solutions to the specific targeted agricultural context.

Knowledge types	Examples	Quotes
Experience-based knowledge through testimonies	Introduce winter bean, rather than spring bean, to avoid the water stress during flowering period	"The benefit of winter beans is greater in soils that tend to be a little dry, the crop cycle is earlier, so it does better, in this period of hydric stress." (D1)
	Testimony of one farmer in another region who stopped using glyphosate	"A colleague coordinating the DEPHY* Network in the Manche region, told me about a particular sheet, describing the cropping system of one farmer in the Haute-Savoie region, in a different context, who had been in a no-till system for 8 years" (D4) *Network of demonstrations, experimentations and productions of references on systems that are less dependent on pesticides
	Testimony of one farmer managing weed in organic farming	"After the switch to organic farming, the only option I could see at the time to manage weeds, was to extend the length of the crop rotation cycle, not necessarily to diversify the crop rotation, but to insert meadow" (D4)
Range of known technical options addressing the same design goal	Identification of technical options to manage a glyphosate-free system	"Here, to start with, we are focussing on the identification of individual farming techniques, before trying to combine them" (D4)
	Comparing the previous effect of lentils, beans and peas	"My question now is about the previous effect of lentils, which is in no way comparable to beans or peas." (D3)
Knowledge on biological object and biological or ecological processes, either scientific-based or experience-based	- Annual rate of decline of rye-grass (*Lolium* spp.) - Rye-grass grows all year round	"Ryegrass, like black-grass, has quite a high annual rate of decline" "If you harvest on July 20th, if it rains a little bit, you have ryegrass coming up right after your harvest... If all conditions are met, it comes up." (D3)
	Flowering time of curled dock *(rumex crispus)*	"Curled dock is adapted to grassland, it's also adapted to mowing, every time you mow it, it grows back. It's able to flower several times a year, so it has no problem with that." (D1)"You can cut it every two weeks, it goes to seed. Over and over again". (D1)
	Selection of nyger due to its drought resistance	"I wanted a plant that would grow well in a drought. It (nyger) is a plant that grows very well in dry conditions. " (D1)
Link biological knowledge with farming techniques	Early harvest of pea to leave time to implement the soil tillage operation while root reserves of thistle are at their lowest	"Peas are actually harvested in late June, so we're into the thistle-sensitive period." (D1)
	Plough depth to fragment roots and lead to exhaustion of curled dock	"Until today, I was used to till plough, with a first found quite shallow. I wasn't working deep on my first round." "Maybe you're cutting into the collar." " Yes, you may have multiplied by cutting into roots." (D1)
	Alfalfa to compete with weeds	"The objective is to use alfalfa, as its large growth allows to compete with weeds" (D4)
	Assess the contribution of faba bean to repel insects	"Will the faba bean sprouts on the row be enough to disturb the insects? Shouldn't we add something else? » (D3)
Interactions between technical options to reach an objective	Combine the introduction of a late-harvest crop and stubble ploughing	"For example, after a pea crop, or a crop harvested very early, it won't be enough to get the thistle, because the thistle has a big root. So you absolutely have to stubble plough first, to get the roots up. And only then can we use the Dyna-Drive." (D1)
	Supply nitrogen to rapeseed and control rye-grass *(Lolium spp.)*	"With this idea of having a favorable previous crop, like a pea or bean, at least a legume, and being able to manage ryegrass, couldn't we imagine something in between, like a cross-cropped clover growing for eight or nine months?" (D3)
Technical option adapted to the global environment	Selection of legumes relatively to the type of soil	"In clay and hydromorphic soil, I believe it's better to grow clover than alfalfa" (D3)

only once the CS had been designed by the rest of the group. Another strategy used by facilitators, consisting in mixing farmers with contrasting objectives or contexts in the same workshop, resulted in broader the discussions (e.g., farmers from organic and conventional systems in D3, from arable crops or livestock production in D1).

3.2.3 Local adaptation of the solutions and preparation of their implementation: Type of reasoning and mobilization of knowledge

After a broad exploration aimed at identifying possible—usually generic—solutions to reach the design goal, designers adapted, or combined practices to suit their local context and its environment, using both scientific-based knowledge and experience-based knowledge (Table 4 including quotes). Most of these adaptations were not known at the beginning of the workshop, but emerged during the design process as the exploration progressed. In some cases, designers discussed the technical compatibility and incompatibility between farming practices to prepare their implementation. For example, designers had considered hoeing winter wheat (D2) or rapeseed (in D3) to reduce the use of post-emergence herbicide, and came back to adapt the modalities of sowing (Table 4). Moreover, they tried to identify and specify the conditions of success or failure of an innovative practice (related to soil and climate conditions, or crop status), with a view to increasing the chances of achieving optimal effects in the new local context. These conditions were sometimes described by a farmer attending the workshop, but at other times they could not easily be identified and were assessed through interactions within the group. For instance, in D1, farmers proposed to sow niger (*Guizotia abyssinica*) in mid-June to prevent the emergence of thistle during intercrop, and through their interactions they found that the niger should be sown early to benefit from the post-harvest soil moisture, right after the harvest of spring pea (a necessary condition to reach a sufficient soil cover to be able to control thistle, Table 4).

In all workshops, to prepare the implementation of a designed solution in a specific field, designers used not only scientific-based knowledge but more frequently also know-how from experience-based knowledge. To do so, they specified the modalities for the implementation of the solutions to suit their local context. Moreover, very often, while determining these modalities, they determined indicators (crop or soil status) related to the optimal conditions for action. For instance, farmers proposed to adapt the cutting frequency of alfalfa to thistle growth status (right before the 6–8 leaf stages, scientific based-knowledge, D1), and the destruction of intercrop with a FACA roller at its flowering stage (D4, Table 4). In our case studies, no tool was used to specifically support the local adaptation of solutions. However, the use of tools (such as the game board) helped designers to develop external representations of the object under design, and to visualize temporal and spatial interactions between practices under design (e.g., farming practices favoring the establishment of the mycorrhizal network in D6).

3.3 Derived features for future design-support tools

Figure 4 summarizes the types of reasoning throughout the design processes studied, and the main ways of mobilizing knowledge that were used by designers and facilitators to support that reasoning: the reformulation of the design goal, the exploration of solutions, and the local adaption of solutions while preparing their implementation. Based on the use of existing tools (Section 3.1.2) and on the observations of design processes (Section 3.2), we identified the following derived features for future design-support tools to guide designers of agroecology-oriented CS: (i) support facilitators to share and capitalize on both scientific-based and experience-based knowledge that is in the spotlight in agroecology-oriented CSs; (ii) promote designers' reasoning, either analogical reasoning or function-based reasoning; and (iii) allow designers to share external representations of the object under design, and to visualize temporal and spatial interaction between practices under design.

4 Discussion

In this section, we discuss the pros and cons of our method (Section 4.1). We then discuss how design-support tools could guide designers and facilitators of design workshop in their activity (i) by enlarging the knowledge basis of the designers to feed design, thus supporting the exploration of new solutions (Section 4.2); (ii) by stimulating their reasonings (Section 4.3); and (iii) by promoting the elaboration of external representations thus empowering all participants of the workshop in the design of a common solution (Section 4.4). We assume that no design-support tool should integrate all features highlighted in our results.

4.1 Learnings and drawbacks from design in workshops

The diagnosis of use situations that we conducted was based on in situ observations of diverse co-design activities that require verbalization, in preference to interviews conducted out of context. Even if observations of design workshops are time consuming, they enabled us to gain access to authentic knowledge exchanges between participants, without any rationalization by the activity designer up front (Visser 1990). At each step of the design process of agroecological cropping systems, before their implementation in real life, we thus identified various types of reasoning (e.g., systemic reasoning required to design

Table 4 Knowledge types used by designers in workshops during the adaptation of solutions.

Knowledge types	Examples	Quotes
Technical compatibility and incompatibility between farming practices	Combine the introduction of lentil and weed scything	"With lentils, you can scythe the taller ryegrass." (D3)
	Adapt the sowing density in order to apply the harrow weeder	"You have to increase the sowing density of rapeseed. The weeding harrow will remove a bit, but you'll keep a good density." (D3)
Conditions of success or failure of candidate practices implemented by others	Early sowing date of niger intercrop to provide more shading	"This is not the first year I've been growing niger. And the earlier you sow, the better." (D1)
	Thistle was regulated here because niger growth was faster after summer rainfall	"In fact, it started growing the day we had a storm. We must have had 15 mm, which is extraordinary for the year. So the niger exploded." (D1).
	Plough depth to fragment roots and lead to exhaustion	"Until today, I was used to till plough, with a first found quite shallow. I wasn't working deep on my first round." "Maybe you're cutting into the collar." " Yes, you may have multiplied by cutting into roots." (D1)
	Destruction of intercrop with roller	"It has to be in the flowering stage to use the FACA, for it to work." (D4)
Practices and combined practices adapted to the local environment	Destroy the meadow in late summer	"We count only on natural drying out of the fields, but you need strong sunshine. And you need to go into the fields as soon as the sun shines, to accelerate the drying out of the plant." (D4)
	Optimal conditions for curly dock growth	"Curly dock likes acidic soils best, so if we raise the pH, the weed will be in a less favorable context." (D1)
	Getting a vigorous rapeseed in a valley	"My goal would be to have a vigorous rapeseed, because it's in a valley, without wind. It's a good place for insects, especially rape blossom beetle." (D3)
Modalities for the implementation of solutions to the local context	Technical modalities to use one "roto-étrille" (from a video shown in the design workshop)	"That means we can use this mechanical weeder both as a harrow or rotary hoe, right after sowing, to enable blind tillage, and set the working depth in order to be above the seed" (D4)
Monitoring indicators	Time to implement the soil tillage operation related to an indicator	"It would be nice if you could have at least three operations in total. Try not to go beyond the critical stage of the thistle, try not to go beyond 6-8 leaves." (D1)
	Destruction of intercrop with roller	"It has to be in the flowering stage to use the FACA, for it to work." (D4)

agroecology-oriented CS, analogical reasoning and function-based reasoning). We also shed light on the diversity of knowledge mobilized by designers, including farmers (e.g., knowledge on ecological and biological processes linked with farming practices, and on biological organisms). Moreover, as design within a workshop is only part of the overall design process, the results we showed did not relate directly to in situ evaluation of the newly-designed solution, but only to the reformulation of the design goal and the exploration of solutions. As shown by Schön (1992), design is also informed by a conversation with the action situation, through the implementation in the field of the CS that was designed in a workshop. This confrontation, managed primarily through step-by-step redesign (Meynard et al. 2012), thus allows the features of the cropping systems to be completed by comparing the prototype to action in the real situation. Such comparison has been shown to be efficient in participatory prototyping trials in West Africa to support farmers' adoption, after adaptation, of innovative legume-based cropping systems (Périnelle et al. 2021). These participatory trials, based on innovative systems identified with a tracking method, seemed to be more effective in motivating farmers to test such innovations on their farms, compared to design workshops. In this context (tropical or developing countries), greater knowledge asymmetry between farmers and scientists hampered farmers' participation in broad exploration during workshops.

4.2 Developing design-support tools for online knowledge sharing

Our results showed that the sharing of a large amount of knowledge fosters the overall design process. Agroecology is indeed based on knowledge-intensive practices (Altieri 2002), and the knowledge needed for agroecological cropping systems design—either generic or situated—is scattered among numerous stakeholders (Girard and Magda 2020). Mobilizing useful knowledge is linked not only to the tool's features but also to the method used by the facilitator to manage the ways of using the tool (Jeuffroy et al., under revision).

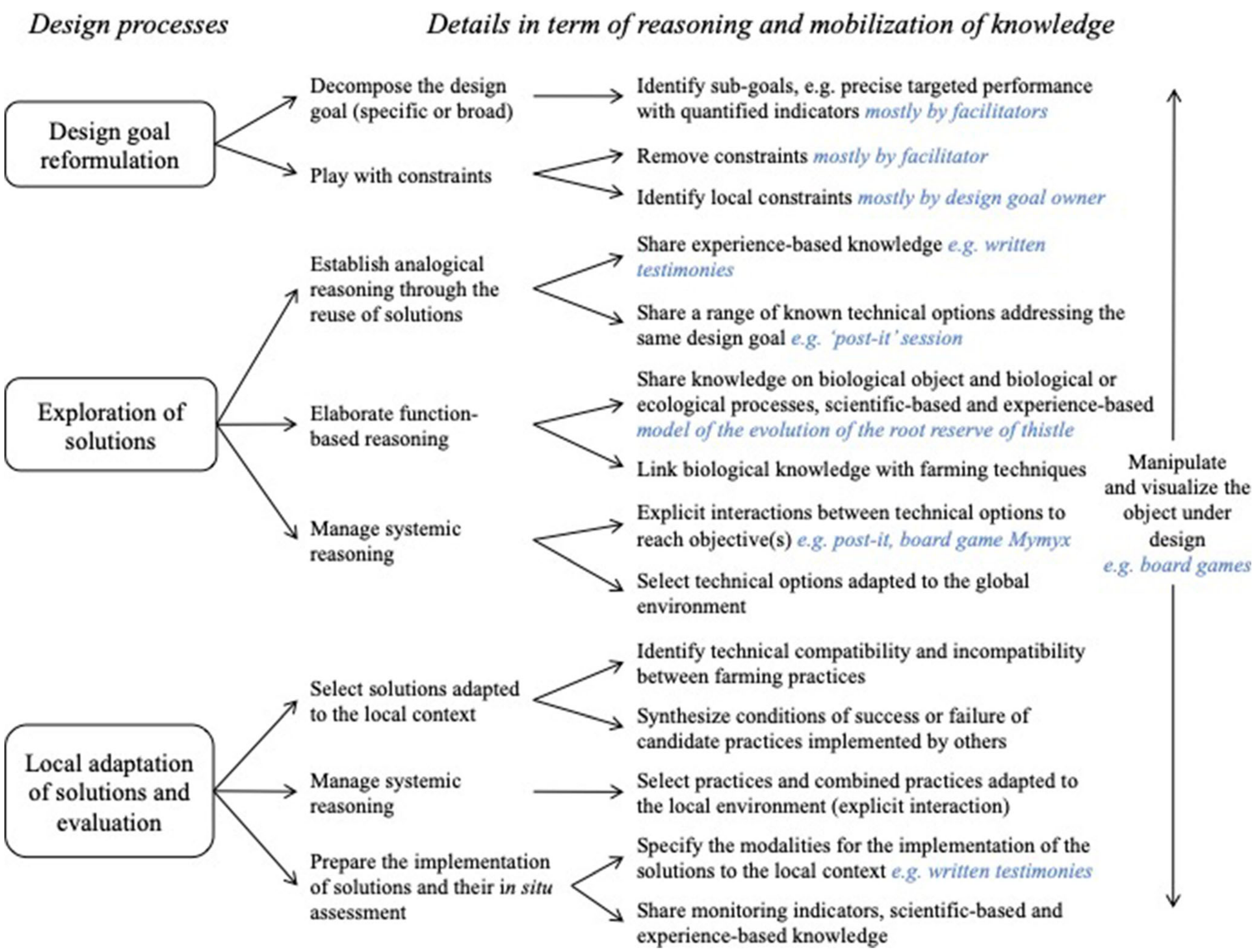

Fig. 4 Synthesis of reasoning and knowledge mobilized by designers during the three interdependent processes of (i) design goal reformulation, (ii) solutions exploration, and (iii) local adaptation of the solutions and their evaluation.

Co-design process may be improved both by supplying design-support tools and by facilitation of the workshop. The workshop format afforded an opportunity to share knowledge among the participants (step 2), but we also identified a need to broaden the areas of knowledge to be considered during a workshop, to foster a larger exploration of solutions (e.g., in D4, a video was shown to share knowledge on specific mechanical tools to control weeds). Facilitators can moreover use design-support tools to bridge designers' knowledge gaps instantly during the workshop (step 3 and 4), thus expanding the knowledge base for design and the grounding required for collective design (Détienne 2006). One example is online tools that widely share knowledge and make it accessible to everyone concerned by agroecological transition (e.g., GECO in Soulignac et al. 2017; Atelier Paysan in Salembier et al. 2021), while gathering distributed knowledge and learnings (Ingram 2008).

4.3 Developing design-support tools to promote the reuse of innovative solutions

Our results showed that designers reuse existing solutions (e.g., either individual practices, or combined practices, or entire CSs) already implemented in local contexts, as a source of inspiration. Analogical reasoning, well-documented in design studies, has been shown to allow designers to expand their pool of ideas, compared to their initial ones (Bonnardel 2000; Détienne 2003). By capitalizing on knowledge on innovative practices, design-support tools could be shaped to enhance the reuse of solutions that have proven to lead to satisfying results for their designers, as Elzen et al. (2017) and Ronner et al. (2021) have already proposed. Such prior solutions, addressing similar goals and already tested by pioneer farmers, can be identified by tracking on-farm innovative practices (Salembier et al. 2016, 2021), system-experiments performed in experimental stations (e.g., Colnenne-David and Doré 2015), or experiments managed by farmers themselves (Catalogna et al. 2018). However, the direct transfer of one CS to another local situation is rarely relevant, due to strong interactions between techniques and the environment, and among techniques. Instead, generally, only some components of the CS are reused and adapted to the new design situation, requiring the initial solution to be described as disassembled in sub-elements keeping their agronomic consistency. Thus, design support-tools should foster the learning of systemic reasoning throughout the design process by describing the agronomic logic underlying satisfying practices, that is, the links between the motives of the farmer, the techniques he/she chose to reach the target, and the assessment criteria he/she uses to improve or stabilize new practices. Such tools should help designers to determine whether a known practice, implemented in the conditions of the new situation, will be likely to produce the expected effects, previously observed elsewhere (supporting decontextualization and recontextualization processes, in Toffolini et al. 2017). For instance, facilitators and designers could rely on cognitive resources during a design workshop (step 2) such as written or video testimonies, from farmers' experiences or from cropping system experiments, or experience-based resources (Quinio et al. 2022). These cognitive resources rely on formalization of the knowledge extracted from these prior experiences in order to explicate and visualize the interactions between the practices that determine the achieved effects and the characteristics of the environment that allow the objectives to be reached.

However, by reusing existing solutions, designers and facilitators can be set on one solution, due to fixation effects (e.g., facilitators are themselves sometimes fixed on the practical solutions they know). Such fixation is well documented in design studies, and refers to a limited range of solutions that designers explore (Jansson and Smith 1991). This raises questions about the efficient knowledge structures in such tools likely to enhance the emergence of innovative ideas (Brun et al. 2016; Le Masson et al. 2016) while allowing knowledge to be updated over time. Moreover, as design workshops are largely promoted and implemented in France (Reau et al. 2012), one way to overcome fixation effects could be to track and share ready-made explorations from previous design workshops, to speed up subsequent exploration by other designers with similar design goals (referred to as design rationale in the literature). For example, generic design-support tools as structured mind maps allow designers to visualize a range of innovative practices, already explored by other collectives, addressing the same design goal (e.g., design step map in Pelzer et al. 2017 or exploration tree in Quinio et al. 2022), or coming from successful experimented systems or farmers' innovations. Similarly, the "Chronicle of Change" method and its underlined tools (e.g., diagram tracing the design problem) have been developed "to keep track of past and ongoing design activity and to generate discussion around it" (Chizallet et al. 2020). Moreover, researchers have shown that sharing examples from other domains and disciplines can be a useful source of inspiration (Bonnardel 2000). In the same way, we found that, in design workshops, mixing farmers with contrasting objectives or contexts resulted in valuable and constructive discussions (e.g., farmers from organic and conventional systems, from arable crops or livestock production), resulting in disruptive innovations. By extrapolation, we suggest that design-support tools should share the solutions of any agricultural sectors (e.g., mixing knowledge from organic and conventional systems) with members of communities of practices (Goulet 2013) that circulate experiences and know-how derived from the implementation of agroecology-oriented CS (Slimi et al. 2021). For instance, Patur'Ajust's online platform is a tool used by a network of livestock farmers (Girard and Madga 2020), and WhatsApp allows farmers to share observations (Slimi et al. 2021).

4.4 Developing design-support tools to promote the construction and sharing of external representations

Design-support tools could help designers to break down the complex design goal into sub-goals that are easier to manage in the design process (e.g., mind map to visualize the refinement of the design goal in step 1), especially when the design goal is proposed by a single facilitator applying rules (e.g., national rule with the banning of the use of glyphosate reformulated in sub-goals as the control of perennial weed without herbicide). This reformulation process, also referred to as problem framing in the literature, was mainly done by facilitators throughout the workshops studied. It was a decisive step, as sharing a common and desired goal between designers was shown to be essential for an efficient collective design (Berthet et al. 2016). Role playing also supported the sharing of representations of the design goal and solutions (Souchère et al. 2010), to put oneself in someone else's place. Designers are asked to play and exchange roles (e.g., advocate, critic): a participant is asked to argue and counter-argue from the ideas of the other group participants (Baker et al. 2020).

As visualization of the complex object under design often appeared necessary during the workshops, design-support tools may furthermore help designers in the construction of shared representations of solutions throughout the design process (Détienne 2006). For instance, tools such as board games help co-designers to refine the object under design, as its numerous components and their interactions can simultaneously be visible (Chave et al. 2019), and thus improved. In disciplines other than agronomy, sketches have been used by architects as tools to share representations of the solution (Brun et al. 2016). Designers visualize and manipulate the objects under design, to express their interpretations of complex solutions and to share diverse intentions and ideas (Safin et al.

2012) in a “reflective conversation” with these external representations (Schön 1983).

5 Conclusion

From a diagnosis of use situations based on real observations during various co-design workshops, we were able to identify the diversity of processes and knowledge uses occurring during these design situations. We thus identified guidelines for future design-support tools to support designers in the redefinition of the design goal, the exploration of ideas, and the adaptation of solutions to the local situation. We also highlighted the major role of facilitators in co-design activity, not only in supporting knowledge sharing but also in guiding reasoning, specifically systemic and analogical reasoning. This questions the extent to which design-support tools should be envisaged, not only as purely technical systems, providing knowledge on demand and guiding various types of reasoning, but also as a system mixing technical and social aspects in which particular roles could facilitate these design processes.

A remaining scientific challenge is the extrapolation of those results outside the design situations in which they were grounded (e.g., individual design, step-by-step design, design of landscape organizations). As the design goal and designed solutions co-evolve in feedback loops between all the interrelated steps of the design process (e.g., the exploration of solutions allows designers to refine the design goal), we wondered how design-support tools could either support the overall organization of the entire process or help facilitators in those tasks. This raises questions of coordination and negotiation between designers, since every step of the design process may not always be carried out by the same stakeholder, depending on their skills and interests.

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