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Diagnosing the socio-technical refrigeration system with Radical Innovation Design methodology to target innovations

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Abstract:

This research aims to address the increasing regulatory and environmental challenges associated with refrigeration systems by fostering innovations. Refrigeration systems, as socio-technical entities, present a challenge due to their complexity, diverse stakeholders, and evolving regulatory constraints. Identifying opportunities for innovation in such intricate systems is further complicated by various performance-contributing factors. The Radical Innovation Design (RID) methodology, designed for aligning design solutions with activities, proves effective in pinpointing and prioritizing innovation targets across the lifecycle of a complex system.

In this study, data from interviews and practices in the retail refrigeration sector inform the RID methodology. Two sets of results are presented. Firstly, a knowledge book of the socio-technical system is categorized into four RID dimensions: usage situations, user profiles, current problems, and existing solutions. The second set includes outcomes from two RID decision-support tools: the RID Comparator evaluates the effectiveness of existing solutions, while the RID Compass identifies three improvement areas - poor adaptation of new technical clusters, disrupted stakeholder interaction processes, and a lack of common tools. These results underwent validation through expert iterations, leading to a recommended hybrid solution involving the development of an integrated model-based platform.

Keywords: Radical Innovation Design, diagnosis, refrigeration, design opportunities

1. Why defining the innovation targets of a complex socio-technical refrigeration system is hard

The impact of climate change on the refrigeration sector has resulted in increasing demand for cooling in the food sector, pharmaceuticals, buildings and transport (Schaeffer et al., 2012). Nearly 20% of all electricity consumption is used for cold production. This figure is expected to rise with growing demand and is predicted to reach 37% by 2050 (IEA, 2018). Refrigeration systems (RSs) are governed by numerous regulations and laws to curb their high environmental impact (Aprea et al., 2012; Islam et al., 2017). Managing an RS from its design to its end-of-life is complex owing to the number of disciplines, stakeholders, roles, and skills involved. The retail refrigeration sector was chosen in the present field study because of its magnitude. This sector represents 3–5% of energy consumption in European countries and is expanding to meet growing demand. In France, retail stores have seen their footfall increase by 10% in 5 years and their number by 8%. Refrigeration equipment (display cabinets or cold rooms) is responsible for 35–50% of the energy consumed by a retail store.

Studies of RSs in retail have mainly focused on developing tools and technologies (Ben-Abdallah et al., 2019), optimizing one or multiple technical performance metrics especially in the design stage under simplified conditions (Ge and Tassou, 2011; Kolokotroni et al., 2019), implementing performance indicators to improve energy efficiency (Acha et al., 2016), and understanding how an RS operates in a supermarket (Bahman et al., 2012). CO₂-based technologies and other energy-efficient solutions such as heat recovery are widely popular in the food retail industry as an advantageous alternative system. Studies have shown that CO₂-based systems have high potential for enhancement (Gullo et al., 2018). However, non-technical issues from the socio-technical RS generate series of poorly addressed requirements that cause problems which, in turn, can lead to sub-optimal system performance. Here we define the socio-technical RS as the set of stakeholders, processes, organizations and technical solutions involved in the activities linked to the RS throughout its lifecycle. Minetto et al. (2018) have conducted a series of interviews of European stakeholders of the food retail sector. Despite a positive attitude toward energy-efficient solutions, the authors identify non-technical barriers to adopting low-carbon solutions such as CO₂-based systems and heat recovery: poor awareness of technological opportunities and expertise in operational optimization, and lack of social, organizational and legislative knowledge. A recently published article (Paurine et al., 2021) also highlights a lack of knowledge, skills and awareness in the industrial use of low-GWP alternative refrigerants. For this purpose, a series of surveys on available training was conducted with several actors in the field. The results showed the usefulness of these fluids, and described the existing practices and the skill needs related to them. To our knowledge, no adequate description or analysis of the socio-technical aspects of an RS in France have yet been undertaken.

Law (2009) defines a socio-technical system as the infrastructure, stakeholders and their roles, technology, regulation, and performance of a system. In Hess and Sovacool, (2020), socio-technical systems are defined as “heterogeneous ensembles of people, artifacts, infrastructures, research, cultural categories, standards and laws, and natural resources”. In Sovacool et al. (2021), a socio-technical approach is used to address climate change challenges from fluorinated greenhouse gases (F-gases). These authors do not merely consider F-gases as by-products; they also address the framework of infrastructure, social institutions and the products that use the gases. In this article, a socio-technical RS includes: the stakeholders and infrastructures throughout the phases of its life cycle (design, use, maintenance, technical update, end of life), the operational environment of the RS, the technical components of the RS (e.g. compressor, condenser, refrigerant), and the laws and standards related to the RS and its performance.

2. Research question and literature review

Our research objective was to identify major areas for improvement of the activities related to the socio-technical RS and the stakeholders' roles, i.e. to get clear and prioritized innovation targets from the diagnostic of the socio-technical RS. From a structural diagnosis, we drew up a prioritized list of improvement paths to innovate in a more integrated design strategy and platform. The purpose of the Radical Innovation Design (RID) methodology (Yannou, 2015; Yannou et al., 2016) is to analyze a complex activity, determine its improvement

paths (called “value buckets”), and use them in an innovative design or management process to increase the performance of that activity. With a comparable aim of analyzing the often low environmental performance of buildings, Lamé et al. (2017) already used RID methodology to analyze the defects in the socio-technical system of specification, design, construction, use, maintenance stages of a building, and the fragmentation in the involvement of the actors, which explained why environmental performance was poor. They were able to show difficulties in implementing lifecycle assessment (LCA), eco-design approaches, and environmental standards, together with the influence of the lack of consultation among the players in this value chain. In another study, Lamé et al. (2018) analyzed the activity system of a dental radiologist to derive value buckets from which they ideated, going on to define innovative socio-technical layout solutions. Bekhradi et al. (2017) investigated do-it-yourself activities to seek an innovative solution for a universal accent light. The utility of following an RID process is discussed by Yannou et al. (2013) and the details of the RID process are given in Yannou et al. (2016).

In the present article, the authors aim to go beyond existing articles to explain in detail the RID problem modeling process, which involves building a cognitive model of the activities linked to a socio-technical RS and analyzing it thanks to two decision-support tools in order to delimit the main areas for improvement or innovation targets upstream of any creativity session. A second objective is to validate that the RID methodology is best suited for this kind of study compared to some alternative methodologies.

A range of methodologies exist for modeling and enhancing complex socio-technical systems, with the most advanced incorporating various modeling and simulation tools. Initially conceptualized by Farel and Yannou (2013), a comprehensive five-stage approach is outlined. This approach involves: (i) the modeling of a socio-technical system, (ii) performance analysis or diagnosis, (iii) identification of key factors affecting moderate performance, (iv) development of potential solution scenarios, and (v) simulation of these scenarios to evaluate performance improvements.

Building on this foundation, Saidani et al (2021) introduced a multi-tool methodology specifically for the recovery of platinum from catalytic converters. This method begins with a material flow analysis (Brunner and Rechberger, 2003) to map the value chain and pinpoint improvement opportunities. Next, it compiles a detailed inventory of influential factors, supported by fuzzy cognitive mapping (Gray et al, 2013) to establish connections between action levers. The methodology then prioritizes key action levers using engineering models and structural analysis, like the MICMAC method (Godet, 2007). The final step involves simulating various scenarios through system dynamics (Forrester, 1961) and comparing these to the original sustainability and circularity performances.

However, this sequence of modeling and simulation is complex, necessitating multiple validations by experts. Moreover, when socio-technical systems cannot be reduced to mere material flows, modeling becomes more intricate due to the various phenomena contributing to the desired performance improvement across the system's life cycle.

In contrast, more qualitative methods like Dependency Structure Modeling (DSM) exist for understanding socio-technical systems' structural properties. DSM, also known as Design Structure Matrix (Steward, 1981; Eppinger and Browning, 2012; Yassine and Braha, 2003), utilizes matrices to represent, analyze, and make decisions regarding product and process systems. DSMs effectively illustrate large amounts of data (Lindemann et al., 2009) and complex system interactions in a straightforward manner. While DSMs have been applied in various domains, such as in solution or supplier selection (Ye et al., 2016), no general framework has emerged like the usage-based reference framework proposed by the Radical Innovation Design (RID) methodology that the authors propose to use in this paper.

The RID process first requires a thorough investigation of a socio-technical RS, yielding a first contribution: knowledge gathering on socio-technical RSs in France. The RID process then segments this knowledge into four dimensions, with categories of stakeholders (called “user profiles”) who experience difficulties or lack of

performance (called “problems”) during their activities, themselves segmented into lifecycle stages (called “usage situations”). The fourth dimension consists of the existing solutions that stakeholders may apply to mitigate or remove a difficulty in a given activity. In an innovation approach, emphasis is placed on value buckets (VBs), for which existing solutions are of little or no help. This knowledge book complements a previously published article (Salehy et al, 2021). The second contribution of this paper is to identify and prioritize innovation targets in a socio-technical RS using two RID decision-aid tools: RID Comparator to first analyze the effectiveness of the existing solutions, and then RID Compass to decide on the innovation targets. In this light, the innovation targets are finally discussed to envisage design specifications of a more integrated model-based design platform for an RS.

Section 2 of this paper describes the RID methodology and our research process. The first contribution is presented in Section 3; the four categorizations of user profiles, usage situations, problems and existing solutions are detailed and justified. The results from the two RID decision-aid tools are commented in Section 4. The effectiveness of the solutions from RID Comparator are first analyzed, and RID Compass then finds improvement paths. Finally, a general conclusion and perspectives are given, with the description of the proposed solution.

3. More on the RID methodology and process of this study

Radical Innovation Design is a novel, complete and well-structured innovative design methodology that prioritizes the improvement of the user experience within a context of activity. RID considers innovative design as the improvement of the activity-support-system to augment the performances of a future activity. Indeed, in Engeström et al's Activity System Diagram theory (1999), the designed solution that serves for supporting an activity is called a mediating artefact (represented as the yellow circle around activity in Figure 1, and is called a Product-Service-Organisation in RID. RID guides innovators who want to systematically explore users' problems and unstated needs, and evaluating which ones are most pressing in terms of innovation, taking into account the effectiveness of existing solutions in contributing to a satisfactory practice of activity. RID renews the way to define innovation targets along with a prioritized set of value buckets in adequacy with company strategy. Value buckets, which are frequent usage situations where major problems are experienced and for which the current solutions provide little or no relief, are qualified questions for usefully start ideation sessions with the guarantee that, if value buckets are cracked, then unaddressed usefulness value is created for users. With its emphasis on problem exploration, RID differs from methods based on early prototyping.

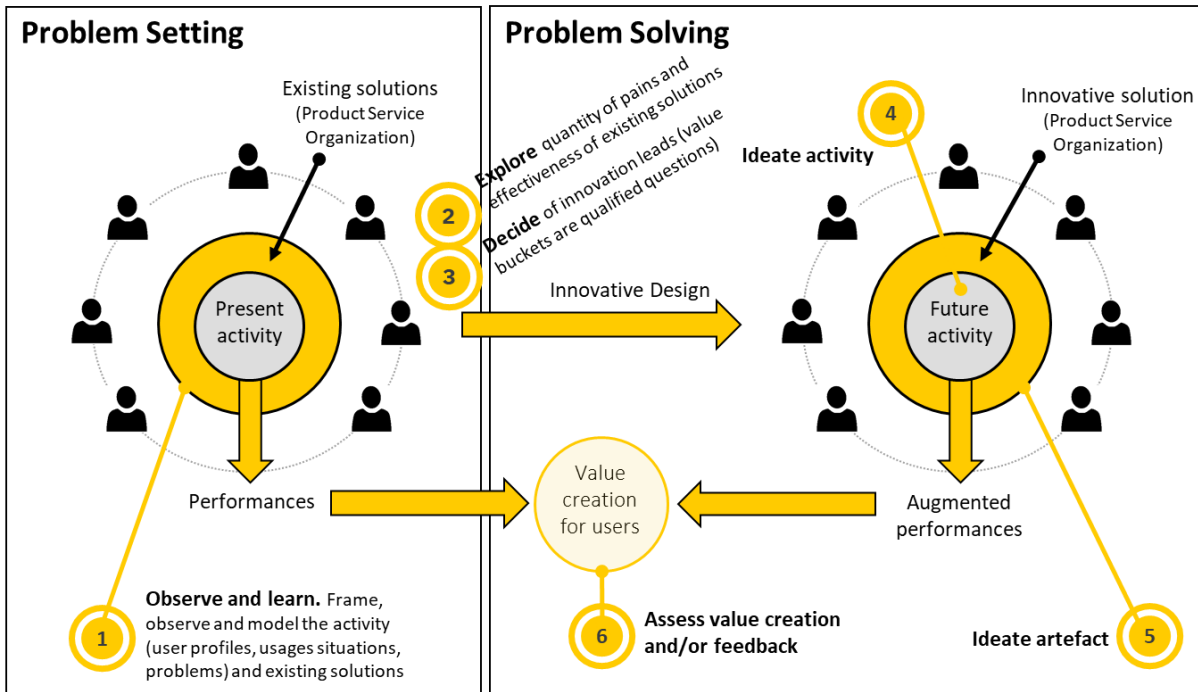


Figure 1. Radical Innovation process: RID considers innovative design as the improvement of the activity-support-system to augment the performances of a future activity.

3.1. More on the RID methodology and process

At a macro level, the RID process has three stages (see Figure 2):

1. Observing the socio-technical system and learning about its current activities, shaping it into a cognitive model,
2. Exploring this cognitive model and deciding on the innovation targets,
3. Ideating, designing and checking that the innovative solutions designed effectively enhance the key performance indicators of the activities.

Here, the authors detail the two first stages for a socio-technical RS.



Figure 2. The three main stages of the Radical Innovation Design process

A more detailed eight-stage, X-shaped process (see Figure 3) represents a production process split into a problem setting part (1) and (2), defined once and for all (for building the cognitive model of current activity), a problem solving process (“ideate and design”) and an “explore and decide” step comprising two decision-making stages and tools, namely RID Comparator to visualize effectiveness ratios and shrink the market space

(i.e., the user profiles, usage situations, and problems) (3), and RID Compass to visualize value buckets and decide the ambition perimeter (4) before moving on to ideation, i.e., starting creativity. The value buckets selected in the ambition perimeter are qualified questions to initiate ideation. After imagining a dreamt or ideal usage scenario (5), new innovative solutions are designed with a new product-service-organization (PSO) architecture (6) and a business model (BM) (7). Finally, a prototype is made (8), experimented in real or virtual conditions for assessing the performance of the activity. RID Comparator is then used again to check the dominance of the innovative solutions within the targeted market space. The most important terms are defined in Appendix A.

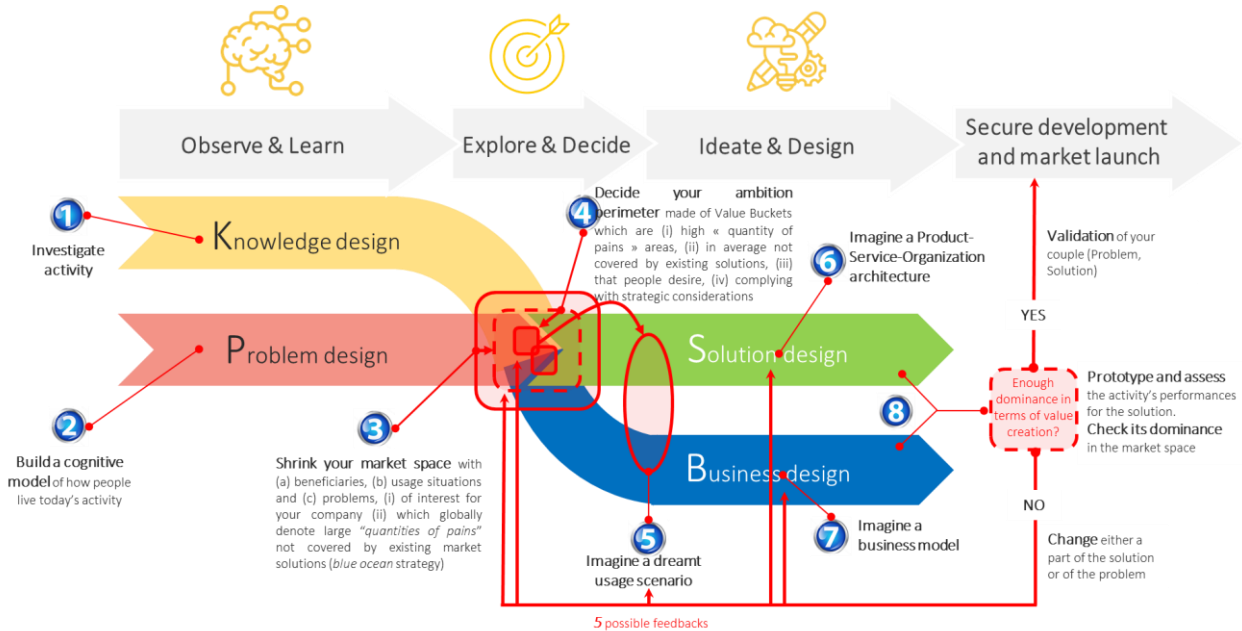


Figure 3. The Radical Innovation Design process in detail

A third process view (see Figure 4) displays the algorithmic workflow for (i) building the cognitive model of activities, (ii) interrogating this model by exploration to better understand its weakest and most desirable aspects, (iii) deciding the part of the overall problem to address (“shrink the market space”) and the precise innovations to target. Building a cognitive model of activities of the socio-technical system of interest requires segmenting four dimensions of activity, namely user profiles (Up), usage situations (Us), problems (P), and existing solutions (Es). After segmenting into meaningful categories, seven matrices (see Figure 4) are filled by semi-quantitative values, answering precise questions. Original algorithms were developed, based on the novel metrics of “quantity of pains” to compute two derived decision-making indicators: effectiveness indicators and value buckets:

- The RID “quantity of pains” is a novel extensive semi-quantitative measurement scale factoring (a size of a user profile) × (a frequency of usage situation) × (an occurrence and gravity of a problem).
- RID Comparator answers the question, "What are the value of solutions (existing and novel) regarding the potential to improve the activity, i.e., eradicate quantities of pains?" Several types of effectiveness indicators are computed to compare the solutions.
- RID Compass answers the question, "What innovations merit development?" within the shrunk market space. Only a subset of strategic value buckets is selected in the ambition perimeter and serve as qualified questions for ideation. Developing a solution from a value bucket guarantees added utility for avoiding or limiting problems during usage situations where competitors are, on average, poorly effective. It precisely orients toward “blue oceans” as described in Blue Ocean Strategy (Kim and Mauborgne, 2005).

In the present paper, we do not provide the algorithmic details and formulas to compute decision-making indicators. The reader will find them in Yannou et al. (2016) and Lamé et al. (2018).

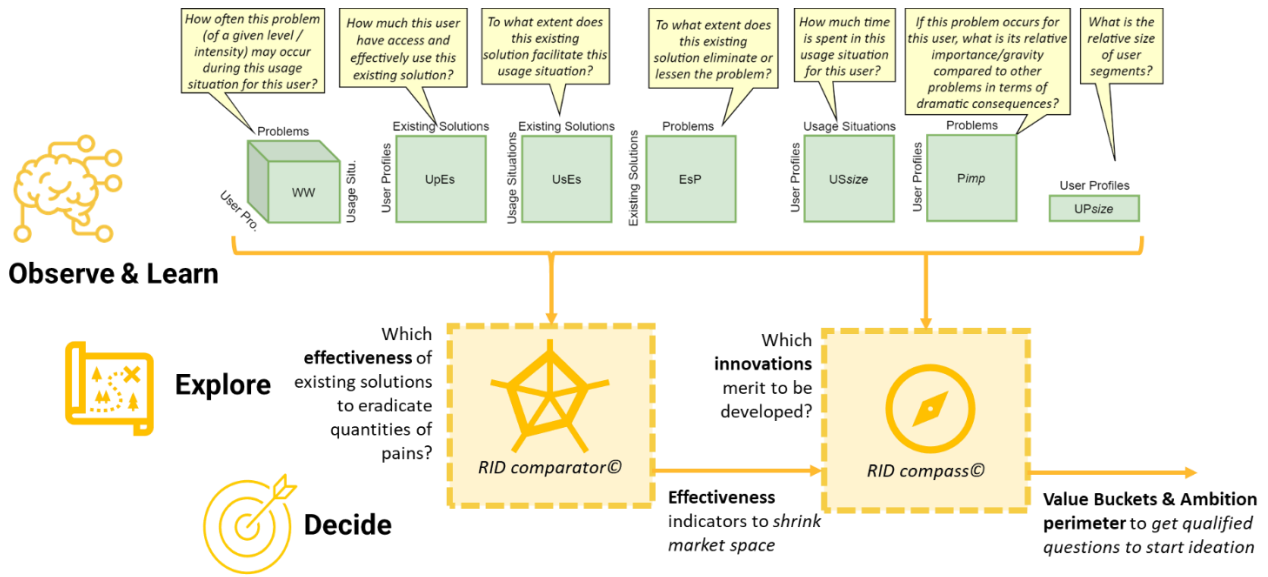


Figure 4. Cognitive perspective and algorithmic workflow of the “Observe and Learn” and “Explore and Decide” stages of the Radical Innovation Design process

3.2. Research process of this study

The first step in our “Observe and Learn” RID stage was an in-depth investigation of the socio-technical RS in France (Stage 1 in Figure 3) before building the cognitive model (Stage 2). We performed (a) a literature review, and (b) a field analysis from observations, interviews and documentation. If no publications were found on commercial socio-technical RS analysis, the study's scope was extended to similar systems such as household refrigerators, buildings and energy systems (Cagno et al., 2019; Hesloin et al., 2017; Lamé et al., 2017; Mignon and Bergek, 2016).

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Fifteen interviews in different companies and disciplines were conducted to collect qualitative data. The interviewees were chosen to be representative of the stakeholders of a socio-technical RS, at different levels of hierarchy, according to their activities and their availability. The interviews took place several times during the process. Firstly, the stakeholders shown in Table 1 were all interviewed once in order to collect data. Once the different categories of user profiles, usage situations, problems, and existing solutions had been identified, the stakeholders were interviewed again to compare the formulation and categorisation of the knowledge book. When the knowledge gathering has been properly constructed and validated, the matrices are built and the algorithm highlights value buckets. In order to validate the priorities identified by the calculations, the stakeholders are interviewed to validate the main conclusions and discuss the solutions to be envisaged. The list of the interviewees is presented in Table 1.

Table 1. Summary of the interviews (role of the interviewees and their organizations)

	Role	Organization	Life cycle phase expertise
1,2,3	Research engineer, PhD	Research lab	Research
4	Research engineer	Research lab	Research
5	Refrigeration engineer	Research lab	Exploitation
6	CEO	Small company	Design, installation, maintenance and exploitation
7	Technical expert in charge of innovation	Large company	Design, installation, maintenance and exploitation
8	R&D project leader & CAD manager	Large company	Design and installation
9	Eco-design expert	Recycling body	End-of-life
10	Teacher	School specialized in refrigeration	Design and installation
11	Refrigeration consultant	Ministry, association	Regulation from installation to end-of-life
12	Research Engineer in Industrial Refrigeration	Large company	Design and installation
13	Business manager	Small company	Installation, maintenance and exploitation
14	Refrigeration expert	Association	Design, installation, maintenance and exploitation
15	Maintenance technician	Small company	Installation, maintenance, exploitation and end-of-life

Each interview lasted about one hour and was semi-guided (open questions were asked). The interviews covered six topics: (i) identity (role, background, position along the value chain), (ii) current regulation and anticipation, (iii) the technology of the systems (limits, skills, development), (iv) the design process, (v) maintenance, and (vi) sustainability positioning (also social and economic concerns). The description of each topic is presented in Table 2.

Table 2. Detailed questions of the interviews

Topic	Expected answers
<i>Identity and Positioning of the actors on the value chain</i>	Background/demographics - General information about the actor and company questioned, including company name, activity, size and geographical location, background, business organization, suppliers and clients, existing collaborations
	Positioning of the actor interviewed on the value chain
	Clarification of the actors, their position and role in the refrigeration industry
<i>Regulatory aspects, including current regulations to be complied with, and anticipation of upcoming regulations</i>	Confirm that the regulation is the main reason for developing a new technology
	Identify potential regulation evolutions
<i>Technology aspects, type of system</i>	Identify and clarify the existing technologies: maps of existing

<i>developed/usually used, limits of their use, why, development of new technologies</i>	solutions → most common ones, why, by who Identify the ways for developing a disrupting technology
<i>Design of a refrigeration system, what are the intermediate design objects</i>	Maps of tools and numerical supports Clarify the needs of design teams for a global approach
<i>Maintenance of refrigeration systems</i>	Clarification of the types of maintenance and the actors involved; From KPIs identified, confront with experts on which are relevant and used
<i>Sustainability issues positioning, including social and economic situations, environmental concerns and ecological transition</i>	Identify the environmental issues positioning of the actors

We have observed during the process that at the beginning of the interviews, the stakeholders expressed reservations about the investigation (mainly due to a fear of revealing confidential information). However, the use of open-ended questions enabled them to gather a great deal of information from their field experience and their growing interest in feeling that they were being listened to. Finally, the conceptualization of their activity, especially highlighting value buckets gave them a systemic vision of their real impacts.

We obtained the two contributions to this “Observe and Learn” (Stage 1 in Figure 2) study. First was a knowledge design part (gathering of the knowledge) on socio-technical RS in France. The knowledge was then computed during the problem design (how to build the cognitive model).

4. Knowledge design of the socio-technical RS

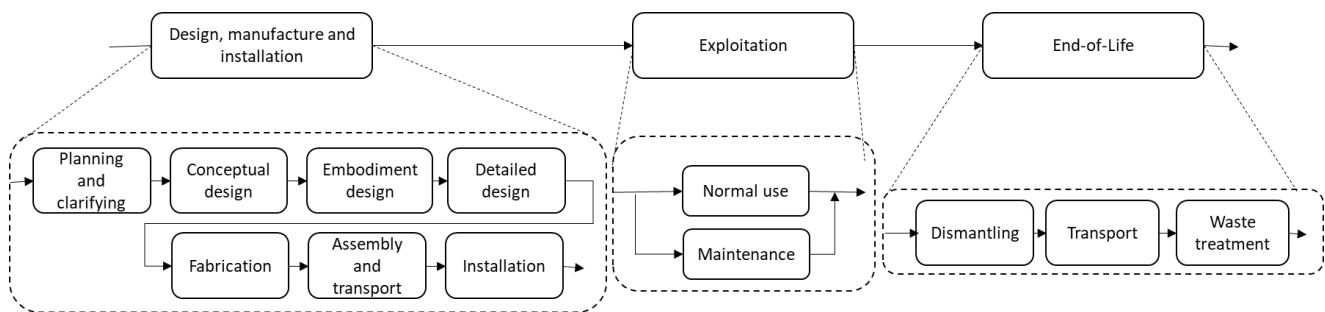
4.1. RS lifecycle process

Based on the data collected during the first step of interviews and a literature review, we ascertained that the main life-cycle stages of a RS were similar to any typical product life-cycle stages (Saaksvuori and Immonen, 2008; Stark, 2016): design, manufacture, installation, exploitation, and end-of-life (EOL) treatment, as depicted in Figure 5. In our study, we consider three main stages for the usage situations:

- **Design, manufacture and installation:** This includes the stages of the engineering design process (Pahl and Beitz, 2013), manufacturing of the RS (including raw material extraction), transport of the components to the installation site, and installation. We aggregated this first usage situation because of the difficulty in clearly distinguishing the boundaries of each of the stakeholders' activities in the initial stages.
- **Exploitation:** This is the longest stage. It includes the regular use of the RS and the attendant maintenance, repair and upgrades.

- **End-of-life (EOL):** This is the shortest stage of the process. It consists of the dismantling, transportation, and EOL management for recycling, reuse, or disposal of the RS.

Figure 5. Retail refrigeration system lifecycle process



4.2. Users involved in the socio-technical RS

Since the signing of the 1987 Montreal Protocol, changing existing installations has proven difficult. In addition, from 2015, the European law on F-gases regulates refrigerants, which are to be replaced by naturally occurring gases in industrial plant by 2030. Experience, knowledge and expertise must thus all be rebuilt in the next decade. This evolution needs flexibility in companies to respond to new regulation. This section provides knowledge of the current stakeholders' organizational process. The semi-guided interviews provide answers concerning the stakeholders' interactions, timeline of the process, what their activities are, and the problems they encounter.

The interviews highlight the fragmented process of managing an RS. The interviewees had different images of the overall socio-technical system, as information is widely scattered, for example on the tasks and activities specific to each stakeholder, or available infrastructure such as EOL treatment choices. They nonetheless answered unanimously on the key roles, the constraints of adapting to the actors they interacted with (budget, deadlines, and company's mindset) and the evolution of the sector.

The twelve identified user profiles and their direct interactions are summarized in an interaction diagram in Figure 6. The users inside the dashed perimeter are the actors directly involved in the design and exploitation of an RS.

During the design stage, the *final user* of the RS (e.g., a supermarket) interacts only with one actor: a *supplier*. The *supplier*, whose role is to link *manufacturing* to final use, is the most participatory stakeholder. The *supplier* also has the specific characteristic of being involved at every lifecycle stage. Once the equipment is installed and running, the only stakeholders concerned by the exploitation stage are the *final user* (as the daily user) and the refrigeration engineers via the supplier for maintenance tasks. In the final stage of the system lifecycle, the activities of *EOL treatment parties* are limited to the transport and treatment (dismantling, recycling, disposal) of the machine. The refrigeration technicians from the supply company oversee draining of the refrigerant from the equipment. The system's *final user* is involved from time to time in the EOL of the system, but this is mostly the *supplier* company's responsibility. Around the project, there is a set of parties that will write regulations, standards and laws, grouped in the Environmental Code in France. The certifications, regulation watch and guidelines are provided by training facilities, unions and associations such as the International Institute of Refrigeration grouped in the category of *professional organisms*.

Academic researchers are also external parties that anticipate new technologies through theoretical and experimental projects. They can be in direct relation with R&D teams or through *technical transfer centers*.

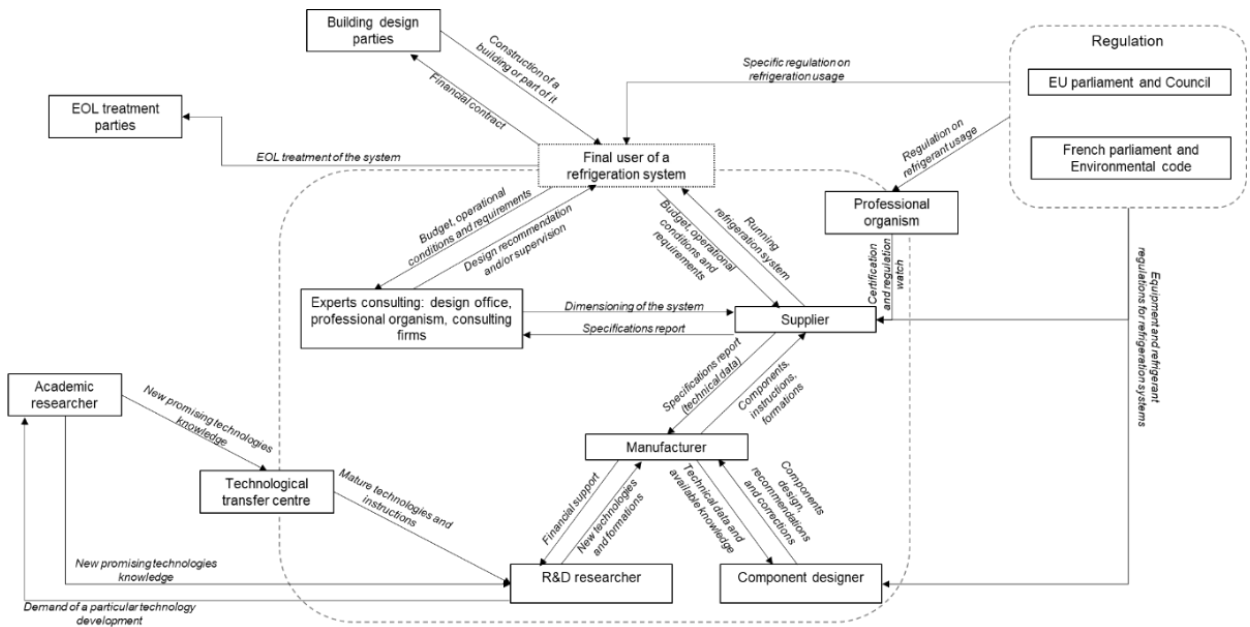


Figure 6. The 12 categories of user profiles and their interactions

4.3. Problems identified in the socio-technical RS

Problems in RID are defined as “issues or lacks of performance experimented by users during usage situations belonging to an activity field” (Yannou et al., 2018). The problems presented in this section stem from the interviews, observations, and literature review. They are either specific to one or common to multiple usage situations. We collected the issues arising in the design and the exploitation phases from the interviews. The end-of-life (EOL) treatment phase gaps are documented by Ardente et al. (2015) and updated with the experts' interviews. During the data treatment and to better understand the underlying phenomenon, a holistic representation of the problems is constructed. Causality graphs serve to organize the data collected into three areas that includes causes, consequences, and problems. Such graphical representation has been made for each of the usage situation. Figure 7 shows the causal graph for the design, fabrication, and installation phase. Figure 8 shows the causal graph for the exploitation phase. Finally Figure 9 shows the causal graph for the problems occurring during EOL treatment phase.

We then placed each of the problems into four main categories: costs (orange boxes in the figures), knowledge management (blue boxes in the figures), interaction between stakeholders (red boxes in the figures), and tools (green boxes in the figures). This problems' categorization is adapted from Pärttö and Saariluoma (2012) and the fifteen main problems highlighted in this study are summarized in Table 3.

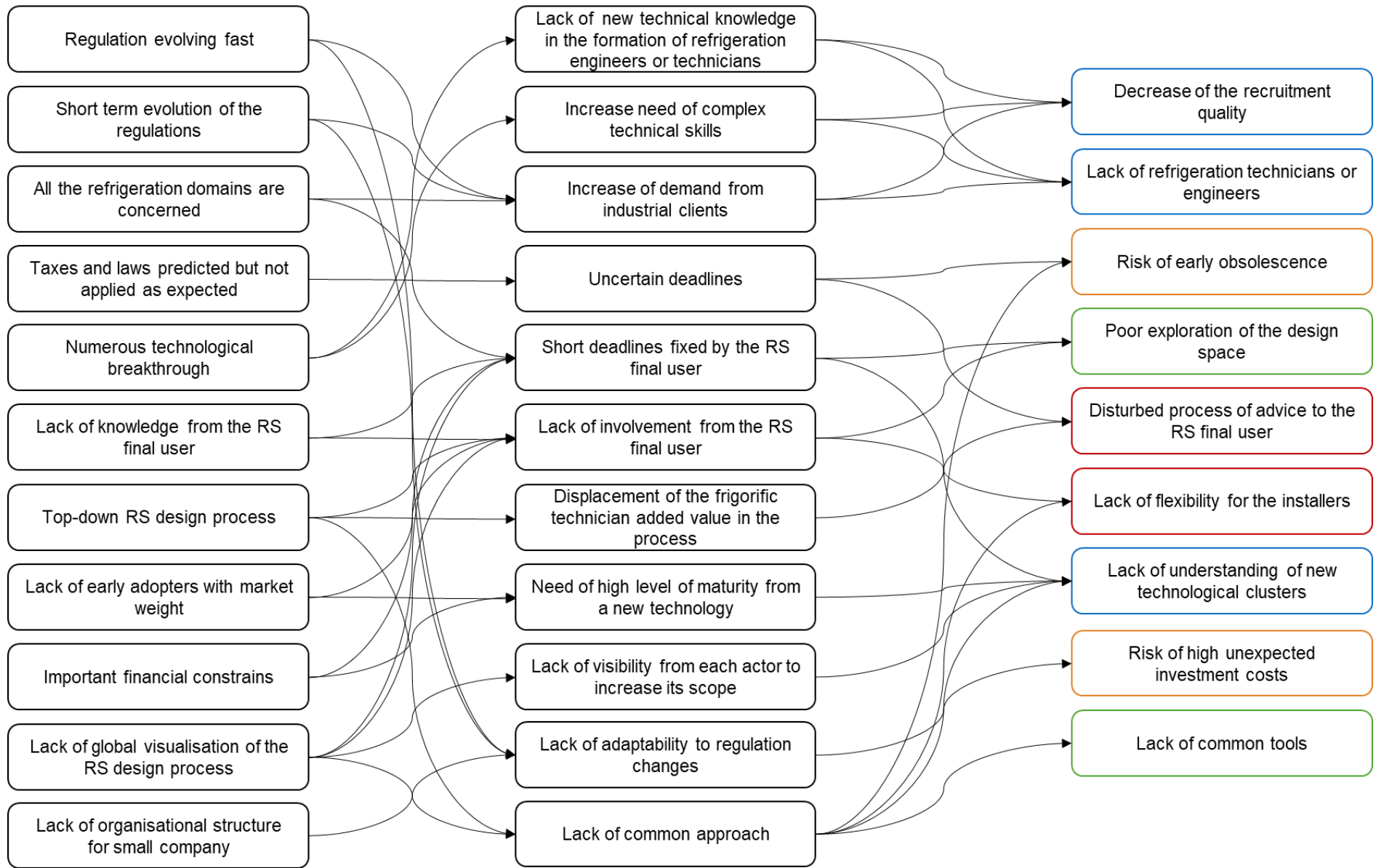


Figure 7. Causality graph for the problems occurring during the design, manufacture and installation phase.

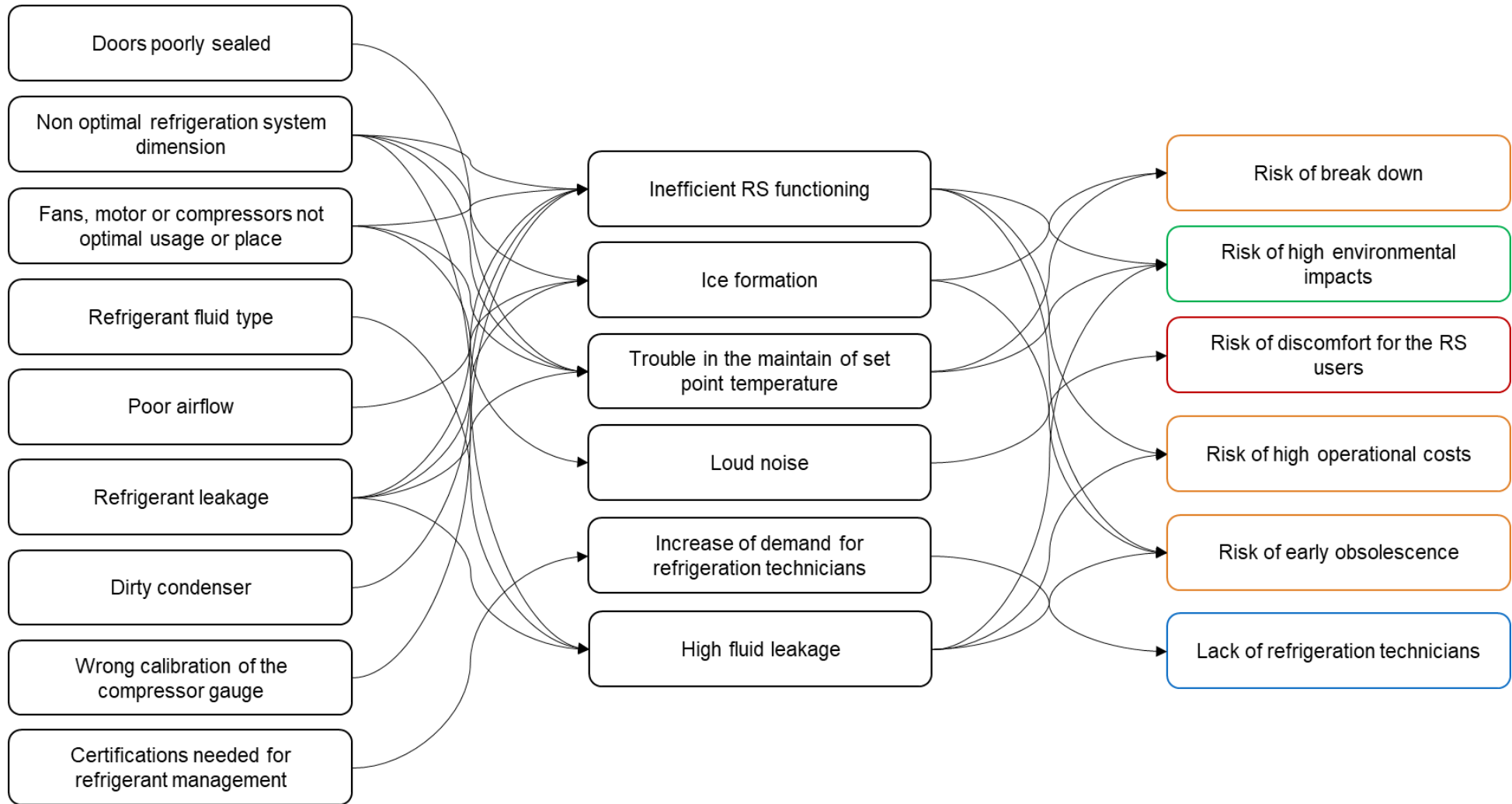


Figure 8. Causality graph for the problems occurring during the exploitation phase.

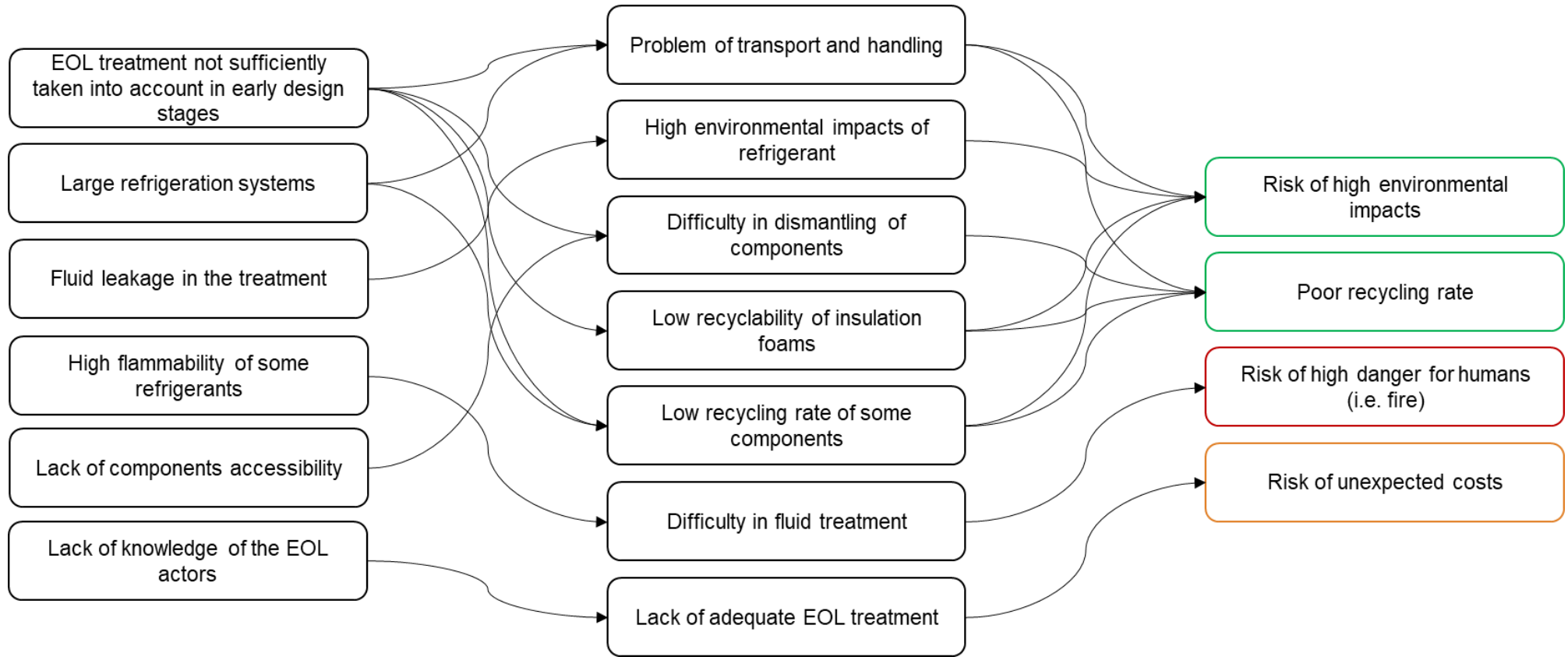


Figure 9. Causality graph for problems occurring during the EOL treatment phase.

Table 3. List of problems identified in in the socio-technical RS and classified in four main categories.

Problem category	N°	Problems identified
Cost	1	<i>Risk of early obsolescence</i>
	2	<i>Risk of unexpected investment costs</i>
	3	<i>Risk of breakdown</i>
	4	<i>Risk of high operational costs (OPEX)</i>
Knowledge management	5	<i>Decrease in the recruitment quality</i>
	6	<i>Lack of refrigeration technicians and engineers</i>
	7	<i>Lack of understanding of new technological clusters</i>
Interactions between stakeholders	8	<i>Disturbed process of advice to the final usage of the system</i>
	9	<i>Lack of flexibility for the installers</i>
	10	<i>Risk of discomfort for the final user's customers</i>
	11	<i>Risk of high danger for human health</i>
Tools	12	<i>Poor exploration of the design space</i>
	13	<i>Lack of common efficient tools</i>
	14	<i>Risk of high environmental impacts</i>
	15	<i>Poor recycling rate</i>

4.3.1. Cost issues

There is a need for rapid change in the systems to respond to the evolution of regulation. The leaders of the refrigeration market (the five largest companies represent 42% of the market) structure the technical advances. A small company will have more difficulty recruiting competent operators for these new developments and keeping up with the latest changes. The lack of structural adaptability in companies makes *the risk of high costs* inevitable. In the exploitation phase, the risk increases with the likelihood of a component's *obsolescence*, human error, and refrigerant leakage. The impact is an *increase in costs*, mostly for the final user. Moreover, the lack of knowledge about the ability of EOL parties to treat their waste sometimes leads to waste being left on-site and so means a poor recycling rate. During the exploitation, *breakdowns* are frequent but not fatal as the system functions remain robust. They can be mechanical, electrical, or design-related breakdowns and can lead to *high repair costs* or *loss of frozen food*. The electricity consumption of the system is the most critical operational cost mainly for maintaining systems and energy loss (Evans et al., 2014).

4.3.2. Knowledge management issues

As the sector is changing, the *training of new technicians or engineers decreases*. As industrial demand increases, the refrigeration sector in France *lacks refrigeration technicians or engineers*. SNEFFCA, a professional union, reports recruitment rate in the sector as more than 4,000 hires per year for 2,000 small or medium companies, with a falling number of applications. In all the usage situations, new technological clusters are often *not fully understood* as there is no time to keep up with the changes

(Minetto et al., 2018). For example, as CO₂-based technologies are deployed, the operators accustomed to HFC systems are faced with pressurized equipment that is new to them.

4.3.3. Interaction issues between stakeholders

Multiple problems of communication between stakeholders were found. The interviews emphasized that a change in regulation results in a *disturbance of the process of advice* for the final user. For example, for air conditioning, the manufacturer is now responsible for the whole lifecycle process. Refrigeration engineers and operators work for the manufacturer and not a supply company. As adaptation times to new standards are not properly allowed for in the final customer demands, the recommendations are not optimal. During the design phase, a frequent problem is that the final user specifications given to the supplier can *constrain the design space*. During the exploitation phase, either during regular use or maintenance, customers can hear an *uncomfortable noise*. This problem is not frequent and does not significantly damage the users but can harm the company's image. Refrigerant use can cause *human health problems* (toxic or flammable refrigerant) or require high-pressure equipment such as CO₂-based systems. Accidents, though extremely rare, can be fatal.

4.3.4. Tool issues

During the RS design phase, most design offices are subject to a strong time constraint that leads to *sub-optimal design space exploration*. More than a hundred types of tool exist to design an RS, but they are *not considered entirely efficient*. Most companies use LCA to calculate the environmental impacts of the systems. The exploitation and the EOL treatment phases carry a greater *risk of higher negative impacts* due to frequent refrigerant leakage and high electricity consumption, resulting in high indirect impacts (Salehy et al., 2019). However, it does not consider the EOL when large industrial systems components are sometimes left on-site mostly because of *higher costs of dismantling* components or *lack of knowledge* of the EOL treatment parties that can manage the EOL.

4.4. Existing solutions

For each of the three usage situations defined previously (cf. Section 3.1), the users have different solutions that can help them accomplish their tasks and mitigate the problems they encounter. We identified six different solution categories:

- **Software-based solutions** comprise the programs and instructions to design and monitor the RS during each usage situation, such as CoolTool (CoolTool Technology GmbH) and Excel spreadsheets.
- **Knowledge management-based solutions** comprise documents, best practices guides, certifications and techniques to guide operators, improve activities, and raise user awareness during each usage situation.
- **Methodological solutions** comprise the methods and approaches used in the design phase to palliate potential problems arising in the exploitation and EOL phases such as Design of X methodologies (Bralla, 1996).
- **Technical solutions** comprise the technical clusters (at all readiness levels). They can include the system architecture, the physical components, digitization, etc.
- **Tool solutions** comprise all the tangible tools used for the RS installation, maintenance, dismantling, and EOL treatment such as a pump for refrigerant or oil draining, or overband magnets for ferrous metal separation.
- **EN 378** groups the standard guidelines (NF EN 378, 2017).

5. Explore and decide the improvement paths of the socio-technical RS

5.1. Data treatment

To summarize, the activities of the socio-technical RS were represented in RID by twelve user profiles (Figure 6), three macro lifecycle stages (or usage situations), fifteen problems (Table 3) and six categories of existing solutions. Seven matrices were then filled with quantifying data on a scale from 0 = never to 5 = frequently, based on the qualitative data collected and following a precise question (see Figure 4).

Table 4 gives an example of matrix filling. It quantifies, from the data collected during the interviews and from observations, the adaptation of the existing solution categories to usage situations. Actors can use a single solution during their activities or a combination of different solutions from the same category or different categories. For example, during the *design phase*, most activities use *software solutions* such as AutoCAD for the system drawings and Excel sheets for the calculation of the frigorific power, compressor needed, and sometimes by the EN378 guidelines and/or *methodological solutions*. *Technological solutions* and *tools* are only used to manufacture components or put the system in place.

It is clear that building an RID cognitive model of activity needs simultaneous answers to a multitude of precise questions but in a qualitative manner, with the rough estimation of an order of magnitude, which is finally easy once the knowledge has accumulated.

Table 4. UsEs matrix: To what extent does this existing solution facilitate the usage situation? (scale from 0 = never to 5 = frequently)

	<i>Software solutions</i>	<i>KM solutions</i>	<i>EN 378 guidelines</i>	<i>Methodological solutions</i>	<i>Technological solutions</i>	<i>Tool solutions</i>
<i>Design, manufacture and installation</i>	4	4	3	3	2	2
<i>Exploitation</i>	4	5	4	4	4	5
<i>End-of-life</i>	3	4	4	3	2	5

As explained in Section 0, we analyzed two sets of results: first the effectiveness indicators computed with RID Comparator, and second the overall matrix of value buckets computed with RID Compass.

5.2. RID Comparator

Figure 10 shows one of the effectiveness indicators: the relative effectiveness of *existing solutions* in responding to the *problems* of a socio-technical RS. It indicates the percentage of possible quantity of pains that each existing solution removes overall in a problem. The most effective solutions are those with the broadest coverage on the radar plot.

Figure 10 shows that the most effective solutions are knowledge-based (training, best practices guides, skills analysis table, etc.) represented in red. *Knowledge management (KM) solutions* include the understanding of new technical solutions such as the use of CO₂ as refrigerant and allow users to engage an effective transition toward regulations (Paurine et al., 2021). The diagram also highlights that the most damaging problems are mainly solved because they represent very high risks for the actors. For example, the risk of high danger for humans is 100% solved by awareness guides and risk analysis, as

is the risk of high operational costs. However, interviewees emphasized that the training courses arrived only after a stakeholder was already in a critical situation (such as working with a CO₂-based system).

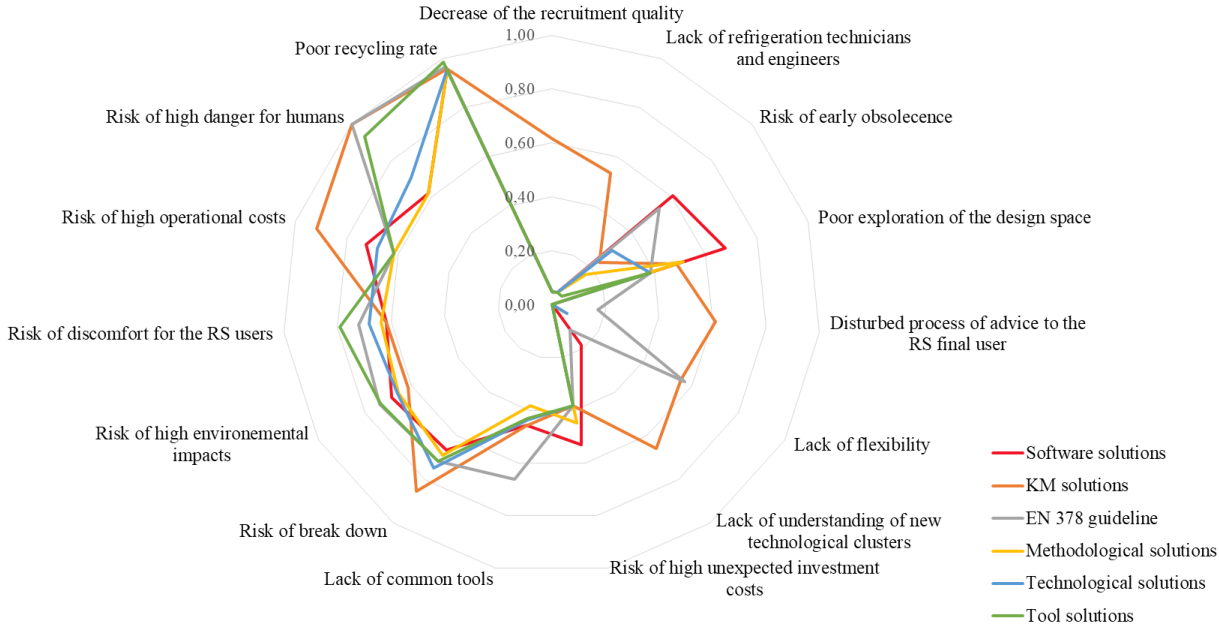


Figure 10. Effectiveness of the existing solutions for the problems (as percentage eradication of quantity of pains, irrespective of usage situations and user profiles)

Figure 11 shows the effectiveness of existing solutions for each of the twelve user profiles. It indicates the percentage of current quantity of pains removed for each user profile. This figure highlights the lack of effective solutions for each user profile. The solutions for academic researchers are underemphasized in this figure. This is because academic research represents a small share of the market compared to other users (manufacturers, designers, suppliers, etc.). Moreover, one of the academic research objectives in refrigeration is to seek the development of alternative technical solutions. The diagram indicates that the stakeholders involved in the process can use a single solution during their activities or a combination of different solutions from the same category or different categories, which confirms the data collected during the interviews.

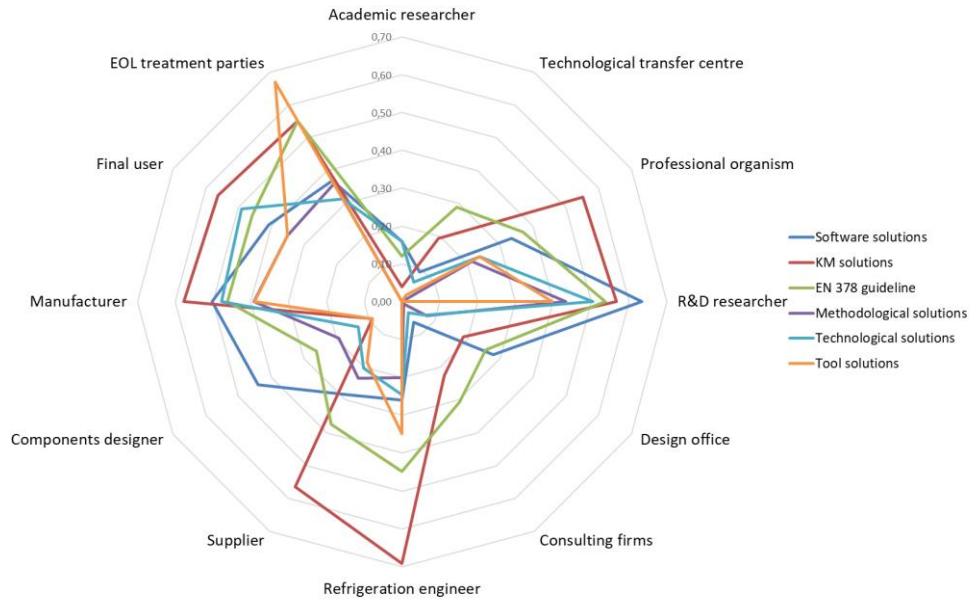


Figure 11. Effectiveness of the existing solutions for the user profiles or stakeholders (as percentage eradication of quantity of pains, irrespective of the usage situations and problems)

5.3. RID Compass

The analysis of effectiveness indicators lets us compare the effectiveness of the existing solutions and thus indicates the percentage of quantity of pains that existing solutions are able to alleviate. The second decision-aid tool (RID Compass) highlights the innovation targets where solutions are not effective on average despite the presence of high quantity of pains.

To explore the improvement paths in the socio-technical RS, we analyzed the global matrix of value buckets shown in Figure 12. The matrix was computed to establish where to innovate to create maximum utility for users when no existing solutions were effective. The highest scores in the matrix highlight the opportunities of development for a competitive advantage, i.e., where competitors have not intensively innovated. Once the matrix is computed, the stakeholders are again asked to validate the value buckets highlighted by the algorithm.

The three most important value buckets occur during the first usage situation, i.e., *design, manufacture and installation*. This is the most complex stage because many stakeholders are involved, each with their own way of acting.

The three VBs identified by the RID Compass algorithm and validated by the interviewed stakeholders (Figure 12) are:

- VB1: *lack of understanding*, i.e., adaptation of the new technical clusters (#7).
- VB2: *disturbed process of interaction between stakeholders*, i.e., the organizational structure in the process (#8,9).
- VB3: *lack of common tools*, i.e., the knowledge shared by all the users involved in the project (including EOL) with a technical cluster database (#13).

The most important VBs occur for problems of *knowledge management and interactions between stakeholders*.

	Cost				Knowledge			Interactions				Tool			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Design, manufacture and installation	0.06	0.05	0	0	0.14	0.28	<u>VB1</u> 0.35	0.34	<u>VB2</u> 0.26	0	0	0.07	<u>VB3</u> 0.35	0	0
Exploitation	0.01	0	0.08	0.02	0	0.09	0.07	0	0	0.05	0	0	0	0.06	0
End-of-life	0	0	0	0	0	0	0.02	0.01	0	0	0	0	0	0.01	0

Figure 12. Results of the RID Compass tool with the three value buckets (VBs) identified.

Even though the interviewees' most crucial performance metric was cost, this does not appear in the value buckets (VBs). The systematic care taken with operational conditions, i.e., regular maintenance, backup mode to prevent complete plant stoppage, and change of non-optimal components, might explain this. Moreover, a national financial incentive such as CEEs (energy saving certificates) in France to change installations encourages companies to improve their systems. The refrigeration sector is one of the first industrial fields to be impacted and made aware of environmental consequences. Accordingly, reducing the system's environmental impacts was not rated as important in the VBs, as the interviewees considered that there were solutions such as ecodesign tools and technologies such as natural refrigerants to reduce emissions.

The EOL was rated the least impactful usage situation. As an RS comes under WEEE, the solutions to manage its EOL once technicians have drained off the refrigerant are highly developed. The only marked challenge for the EOL parties is the need to be informed of any disruptive technical change. They need to be aware of technological developments if EOL management changes.

During the exploitation phase, the system robustness influences the problems encountered. As RSs are robust due to extensive research on system optimization, interviewees did not indicate this stage as the most challenging one. However, as summers get hotter, more and more systems run at least once in their back-up degraded mode. In the years to come, refrigeration technicians and project managers consider that they will have to face the problems of providing a system that can run at peak cold need (typically on the hottest day of the year).

More than a hundred tool solutions exist. However, the effectiveness indicators of the solutions presented in Figure 10 and Figure 11 show that they do not fully address the current industrial problems. Moreover, the problems of knowledge management and interaction between stakeholders do not have many possible solutions. This is one of the issues most difficult to manage for the interviewed user. We observed a confusion among the stakeholders about the whole socio-technical system, mostly because of the large number of companies, regulations, solutions, and possibilities.

Applying the RID process revealed the importance of the design, manufacture, and installation phases. The interviewees considered this usage situation as the most challenging one: it is then that multiple actors from different companies or teams collaborate, bringing their knowledge, preferences, tools, and experience.

Knowledge management and interaction between stakeholders are two important problem categories identified by Pärttö and Saariluoma (2012) that explain failures in design. In the last decades, research in refrigeration has developed promising technologies. The stakeholders meet difficulties investing in these new technologies because of lack of long-term visibility. RSs are robust and costly to develop. Technical change toward more sustainable systems should be more usage-driven in the future, with more systematic consideration of the users and the usage situations of the whole socio-technical RS.

Following the present study, we intend to address the gaps identified with the main value buckets by two novel solutions to improve the performance of the activities of the socio-technical RS. First, by developing a new model-based integrated design platform and approach. It has been recently done and published in (Salehy et al, 2023), demonstrating an excellent performance. Indeed, the approach considers both new technology and the complexity of the socio-economic environment for effective industrial implementation. Thus this solution enable industrial stakeholders to better understand the potential of innovative technologies (VB1 and VB2). Second, by fostering a new organization linking all the stakeholders involved in the early stages of an RS design. This solution has been thought out in line with the value buckets and the reflection has been fueled by discussion with the stakeholders.

To close the loop of the RID methodology, the ability of our two solutions to fully act on identified value buckets will be assessed by comparing, using RID Comparator, our solution with the existing ones.

6. Conclusion

This paper had two goals. The first one was to enhance the design of refrigeration systems (RS) used in supermarkets. This involved diagnosing the RS throughout its lifecycle and pinpointing key innovation targets. The identified issues in RS performance are primarily due to inadequate tools, lack of design expertise, and organizational challenges stemming from insufficient communication among value chain stakeholders.

The second goal was to demonstrate the suitability of the RID methodology for identifying and prioritizing innovation targets in complex systems like RS. The paper details the RID problem modeling process, which includes building a cognitive model of RS-related activities and analyzing them using two decision-support tools. This process helps identify areas for improvement or innovation early on, which is more effective than multi-tool or Design Structure Matrix (DSM) approaches.

The paper includes a case study on the French refrigeration sector, applying the RID methodology for open-loop innovation. This involves gathering field information to understand stakeholder information flows and dysfunction points. The RID methodology's first two stages are used to formalize and classify this information and identify significant gaps in existing solutions.

The study identifies critical points in the RS lifecycle, particularly in design, manufacture, and installation phases, where different actors are involved but lack interaction. Three main stakeholder problems are highlighted: understanding new technologies (VB1), the absence of a common tool meeting all stakeholders' expectations (VB2), and inadequate interaction among stakeholders (VB3). These outcomes corresponds to clear issues raised by various stakeholders during the ground research.

The paper proposes a two-pronged innovative solution: (i) an integrated model-based design platform for RS, and (ii) a new organizational structure for the RS lifecycle. This first integrated platform, whose aim is to to better incorporate stakeholder constraints and objectives, has been developed and tested. A recent publication (Salehy et al, 2023) demonstrated its ability to enhance understanding of new technologies by enabling broader explorations of solution architectures and dimensional spaces, and creating value for SR stakeholders by enabling them to design by specifying ranges of expected performance (Salehy, 2022). In addressing these VBs, the proposed solutions rely on knowledge management methodologies (design model and platform), which can be found in other domains, such as mechanical engineering.

Nomenclature

CEE: Certificat d'Economie d'Energie (energy saving certificate)

EOL: end-of-life

Es: existing solution

F-gas: fluorinated greenhouse gas

KM: knowledge management

LCA: lifecycle assessment

P: problem

RID: Radical Innovation Design

RS: refrigeration system

Up: user profile

Us: usage situation

VB: value bucket

WEEE: waste electrical and electronic equipment

Declaration of interest statement

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

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Appendix

Appendix A. Glossary

Name	Definition
<i>Ambition perimeter</i>	A subset of important value buckets that people also desire, complying with strategic considerations (core competencies, brand image, expected benefits, technological and market roadmaps, easiness to develop, etc.).
<i>Business model (BM) solution</i>	The plan for creating, delivering, and capturing the value from a PSO architecture.
<i>Cognitive model of activity (after RID)</i>	A simplified representation of how an activity is lived by some user profiles (here RS stakeholders), facing some problems or lack of performance during usage situations (here RS lifecycle stages), and for which existing solutions are variably effective.
<i>Dreamt usage scenario</i>	A usage scenario of the future desired activity where the entire solution is not represented but its desired effects are illustrated in narrative form.
<i>Effectiveness indicators</i>	Set of indicators given as a percentage, expressing the ability of solutions (existing ones or the innovative one) to eradicate a part of the quantities of pains for some problems or for some usage situations.
<i>Ideation</i>	Process of generating new ideas. In RID, a first “scenario creativity” session transforms value buckets into one or several dreamt usage scenarios, and a second “solution creativity” session transforms a dreamt usage scenario into a PSO architecture and a BM solution.
<i>Product-service-organization architecture (PSO)</i>	A cohesive solution of product, service and organization (the network of stakeholders that operates the product-service system)
<i>Quantity of pains</i>	Quantity of pains is an original extensive semi-quantitative measurement scale made of (a size of a User Profile) × (a frequency of Usage Situation) × (an occurrence and gravity of a Problem).
<i>Radical Innovation Design (RID)</i>	RID is a methodology to innovate on (i) an activity from the viewpoint of its beneficiaries or (ii) on a technical component’s role from the viewpoint of the system performance. It is a Design Thinking process with visual management facilities, decision-making tools, together with a project and knowledge management facilities.
<i>Socio-technical RS</i>	Set of stakeholders, processes, organization and technical solutions involved in the activities linked to the RS along its lifecycle phases (design, manufacture, use, maintenance, technological updates, end of life).
Value bucket (VB)	A major problem (with serious consequences) for a given user profile that arises during a frequent usage situation and for which existing solutions provide too little or no relief