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Benefit-risk analysis of prospective scenarios implementing new-generation food safety management technologies: Qualitative, stakeholder-driven study of the infant food chain☆

Rallou Thomopoulos[a,*], Romy Lynn Chaib[b,a], Gaud Dervilly[c]

[a] IATE, Univ Montpellier, INRAE, Institut Agro, Montpellier, France
[b] Ch. Gillet Society, Villeneuve-les-Maguelone, France
[c] ONIRIS, INRAE, LABERCA, Nantes, France

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ABSTRACT

This paper examines the potential impact of introducing new hazard detection, control, and mitigation tools in the infant food chain by conducting a qualitative and stakeholder-driven benefit-risk analysis of prospective scenarios. The scenarios envision the possible implementations of the tools and approaches developed in the 'Safe Food For Infants' (SAFFI) Europe-China project, which include detection technologies, hazard control and mitigation strategies, as well as models for hazard identification and risk ranking. The objective is to evaluate how the implementation of these tools could affect food safety management, particularly in light of diverse consumer behaviors, evolving technologies, and regulatory contexts. Through a scenario-building approach, the paper constructs potential futures for the infant food chain, followed by a detailed benefit-risk analysis. The analysis incorporates a variety of stakeholder perspectives and criteria, including safety, economic impact, and technological advancements. The findings provide valuable insights into how different strategies for hazard control and mitigation may improve food safety, while also considering the trade-offs associated with these strategies. The paper ultimately proposes a global ranking of scenarios based on a collective attitude score, offering a comprehensive evaluation of prospective futures for infant food safety.

1. Introduction

Ensuring food safety in the globalized and increasingly complex food supply chain presents a significant challenge, particularly when it comes to high safety standards intended for a vulnerable population, as it is the case for infant food (ANSES, 2016). This complexity is due to several factors, highlighted in Engel et al. (2022). Indeed, the wide range of raw materials, processing methods, packaging and storage techniques lead to a wide range of products (Stella et al., 2013). Besides, the changing and diverse consumer behaviors can also be sources of risks (Tonda et al., 2023). In addition, innovations in agriculture and food technology, new findings in human health with evolving regulations influence the continuous development of products (Bokulich et al., 2016). Finally, the disparities in regulatory frameworks and health monitoring systems across different countries, especially in the context of global trade, create a broad spectrum of potential hazards that must be addressed (FAO, 2017). As a result, identifying, controlling, and mitigating food safety risks remains a highly dynamic and multifaceted task.

In this context, the development of new hazard detection and control tools, as well as improved risk modeling techniques, offers promising opportunities to enhance food safety (Rantsiou et al., 2018). The EU-China project 'Safe Food For Infants' (SAFFI), designed to collaboratively address these challenges, has studied a set of innovative tools aimed at improving the detection, identification, and mitigation of food safety risks (Engel et al., 2022). These tools are intended to provide a more proactive and data-driven approach to food safety management, particularly in the context of infant food production. However, the introduction of these tools into the food supply chain raises critical questions about their overall impact on food safety outcomes, economic viability, and stakeholder perspectives.

Let's imagine and analyze what could happen in the food chain if the new detection tools, hazard control and mitigation strategies, and

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* Corresponding author at: INRAE – UMR IATE, 2 place Pierre Viala (bât. 31), 34060 Montpellier cedex 1, France.
E-mail address: rallou.thomopoulos@inrae.fr (R. Thomopoulos).

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models for hazard identification and risk ranking, developed in SAFFI, were available on the market? The paper seeks to address this question by conducting a benefit-risk analysis of prospective scenarios in which these new tools are implemented. The objective is twofold: first, to explore the potential effects of these tools on the infant food chain by constructing plausible scenarios; and second, to evaluate the benefit-risk implications of these scenarios from the standpoint of various stakeholders involved in food safety management.

The analysis presented in this paper is grounded in two methodological approaches: scenario building and benefit-risk analysis. Scenario building, specifically through the use of the so-called "scenario method" (Godet, 2008), allows for the construction of a variety of future pathways that reflect the complex interactions between different variables influencing food safety. These scenarios are then subjected to a benefit-risk analysis, using the argumentation-based approach and tool *MyChoice*® (Thomopoulos et al., 2020) to support collective decision analysis, which takes into account a wide range of stakeholder perspectives and criteria. This approach allows for the evaluation of the relative advantages and disadvantages of each scenario, with the goal of identifying the most promising strategies for improving food safety in the infant food chain.

The paper is structured as follows: Section 2 outlines the methods used to construct the prospective scenarios and to conduct the benefit-risk analysis. In Section 3, the results of the scenario-building process are presented (part 3.1), including the identification of key variables and the selection of five plausible scenarios; then the results of benefit-risk analysis of these scenarios are provided (part 3.2), considering the viewpoints of stakeholders from various sectors, including research, safety authorities, and the food industry. Section 4 concludes with a summary of the key findings and insights drawn from the analysis, including recommendations for future research and policy considerations.

By providing a structured and comprehensive analysis of the potential impacts of new hazard detection, control, and mitigation tools, this paper aims to contribute to the ongoing dialogue on how to improve food safety management in the context of an increasingly complex and interconnected global food system. The insights presented here are intended to inform both research, policymakers and industry stakeholders as they navigate the challenges of ensuring the safety of infant food products in a rapidly changing environment.

2. Material and methods

2.1. Scenario building

The method used for scenario building is the so-called "scenario method" (or Godet method). The characteristics of this method, which drove this choice, are explained hereafter.

Prospective methods use scenarios, defined as conditions of important variables at a given time, and stemming from the evolution from current conditions to other futures (Pesonen et al., 2000). Different types of scenarios have been defined, predictive, explorative or normative (Börjeson et al., 2006; Marini & Blanc, 2014). The "scenario method" is one of the classic prospective methods well-suited for a use in food chain studies. It is a participatory method, it is therefore based on the interactions between different stakeholders involved (Godet, 2008; Godet & Durance, 2001). Over the years, this method has been successfully applied to numerous sectors at different scales (Duperrin et al., 1975; Lesourne et al., 1986). It has proven to be relevant when applied in the agri-food sectors (Chaib et al., 2021, 2022a, 2022c). The essential principle is to design scenarios of possible evolutions of the system studied.

Engaging participants guarantees that the scenarios identified are relevant to the food system's stakeholders (Arce-Gomez et al., 2015; Becker et al., 2003, 2004). Stakeholders may have heterogeneous opinions and priorities related to different criteria (economic, social, environmental, sensory, technical, sanitary, etc.…) (Funtowicz et al., 1999; Rosen, 1977). Thus the food chain system cannot be captured using a single perspective (Brugha & Varvasovszky, 2000; Munda, 2004). Co-designing plausible futures for the value-chain is in a context of collaborative modeling as described in Basco-Carrera et al. (2017).

The steps we followed for the scenario method were:

- Grouping the actors and collectively discussing the variables that are likely to influence the evolutions of the system studied. In our case, this step was performed through the "SAFFI joint working groups" workshop, organised during SAFFI 3rd annual meeting in the form of a "world café". Joint working groups involving both EU and China partners, with the objective to explore jointly the plausible scenarios of hazard control systems for infant food and to predict their impact for the stakeholders (public authorities, infant food sector and consumers). Four working groups were organised to successively discuss (i) hazard focus, (ii) control strategies, and (iii) detection technologies, while working group (iv) was a collective discussion on the feasibility of scenarios defined as combinations of the previous points.
- Building cognitive maps from the outcomes of the working groups. These maps have two purposes:
  - identifying the concepts that the participants consider relevant to describe the future of the system;
  - designing the influence relationships between these concepts.
- Determining the key variables of the system, which implies to:
  - group the concepts into a limited number of more general variables;
  - compute the influence and dependence of each variable;
  - deduce the key variables, defined by their high level of both dependence and influence.
- Building the scenarios through the following steps:
  - combining the values of the key variables;
  - reducing the number of combinations to the most relevant ones;
  - choosing the scenarios to be more precisely described.

In the case of the SAFFI project, our goal is to envisage the plurality of futures of the implementation of new hazard detection, hazard control, and risk modeling tools, in the infant food chain. Our initial materials being the outputs of the "SAFFI joint working groups" workshop, for each working group we drew a cognitive map, which links the concepts mentioned by causal links cited by the actors. Then we calculated the number of links which started from (links of influence) or which led to (link of dependence) each concept. Finally, we grouped the concepts into more general ones, denoted by "variables" in the scenario method (e.g. safety-related, economic, technological variables, etc.), in order to obtain the influences and the dependences of these variables. Variables that are both more influential and more dependent than average are the so-called "key variables". Each can take several values – two contrasted values in our approach. For example, for variable D "Type of tools developed": D1 for targeted tools; D2 for untargeted tools. These values are taken from the analysed speeches. By combining all the values that can be taken by each key variable, we obtain a tree that describes the possible scenarios. In the case where there are N key variables, each admitting 2 possible values, we end up with 2^N possible scenarios. After elimination of scenarios that combine incompatible values, and grouping of similar scenarios, we obtain a restricted number of scenarios to be further studied – five in the present study.

2.2. Benefit-risk analysis

The method used for benefit-risk analysis is based on the *MyChoice* software (Thomopoulos et al., 2020) developed and released by INRAE. It has been applied to various contexts especially in the agri-food sector (Chaib et al., 2022b; Vivas et al., 2022; Kurtz & Thomopoulos, 2021). The inputs of the method consist in a list of arguments describing the

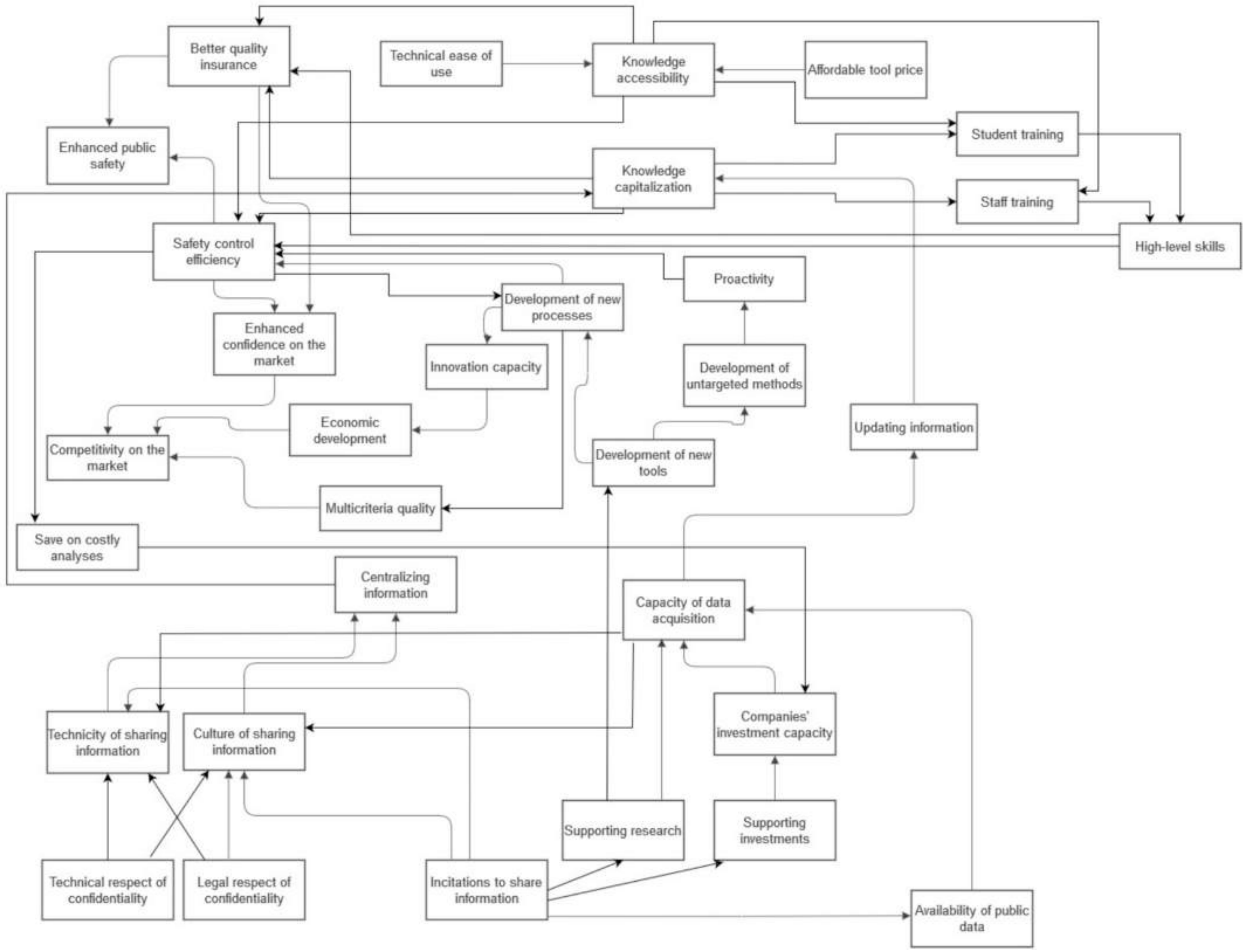

Fig. 1. Cognitive map built from the outputs of Working Group 1 "Hazard identification and risk ranking". We suggest starting the reading of the figure from the bottom concepts, which influence the rest.

benefits and limits identified for the five scenarios presented in the previous section, through the viewpoints of different criteria and different stakeholders.

The *MyChoice* software is based on the general theory of argumentation in Artificial Intelligence (Dung, 1995), whose fundamental principle is to represent a set of arguments and contradictions between them – denoted as "attacks" – then to compute subsets of arguments that satisfy some coherence principles. Argumentation is thus a reasoning model based on the construction and the evaluation of interacting arguments. In decision-oriented approaches (Amgoud & Prade, 2009), an argument is a statement that justifies or counters an alternative in order to accomplish an objective. In multi-criteria oriented works, such as those considering food chain analysis, this objective refers to a criterion used as a viewpoint or dimension in the analysis (Thomopoulos et al., 2020). Several authors proposed different ways of incorporating argumentation in multi criteria approaches in the aim of providing an explanation behind the decisions taken (Bourguet et al., 2013; Thomopoulos & Paturel, 2017; Bisquert et al., 2017; Salliou & Thomopoulos, 2018; Karanikolas et al., 2018; Thomopoulos, 2018; Sohn et al., 2020; Thomopoulos et al., 2020).

Compared with the classic approach, the *MyChoice* tool has several important specificities chosen for adequacy with its applied objective. The most salient ones are:

- A detailed description of arguments, with a database-oriented approach. Concretely, this is materialized by numerous information composing each argument:
  - Which scenario does the argument refer to?
  - Does it express an idea in favor (positive argument) or against (negative argument) the scenario?

This point is denoted as "bipolar" approach, also proposed in previous decision-oriented argumentation frameworks (Amgoud & Prade, 2009).

- For which type of stakeholder? (research labs, safety authorities, SMEs of the food sector, large-scale companies, etc.)
- According to which criterion? (safety, technology, environment, economy, etc.)
- What aim in that criterion is more specifically considered satisfied/unsatisfied?

E.g. in the "Economic" criterion, such aims can be "Ensuring business viability", "Meeting the requirements of high safety-demanding markets", etc.

- What characteristic of the scenario is considered favorable/unfavorable in this argument?

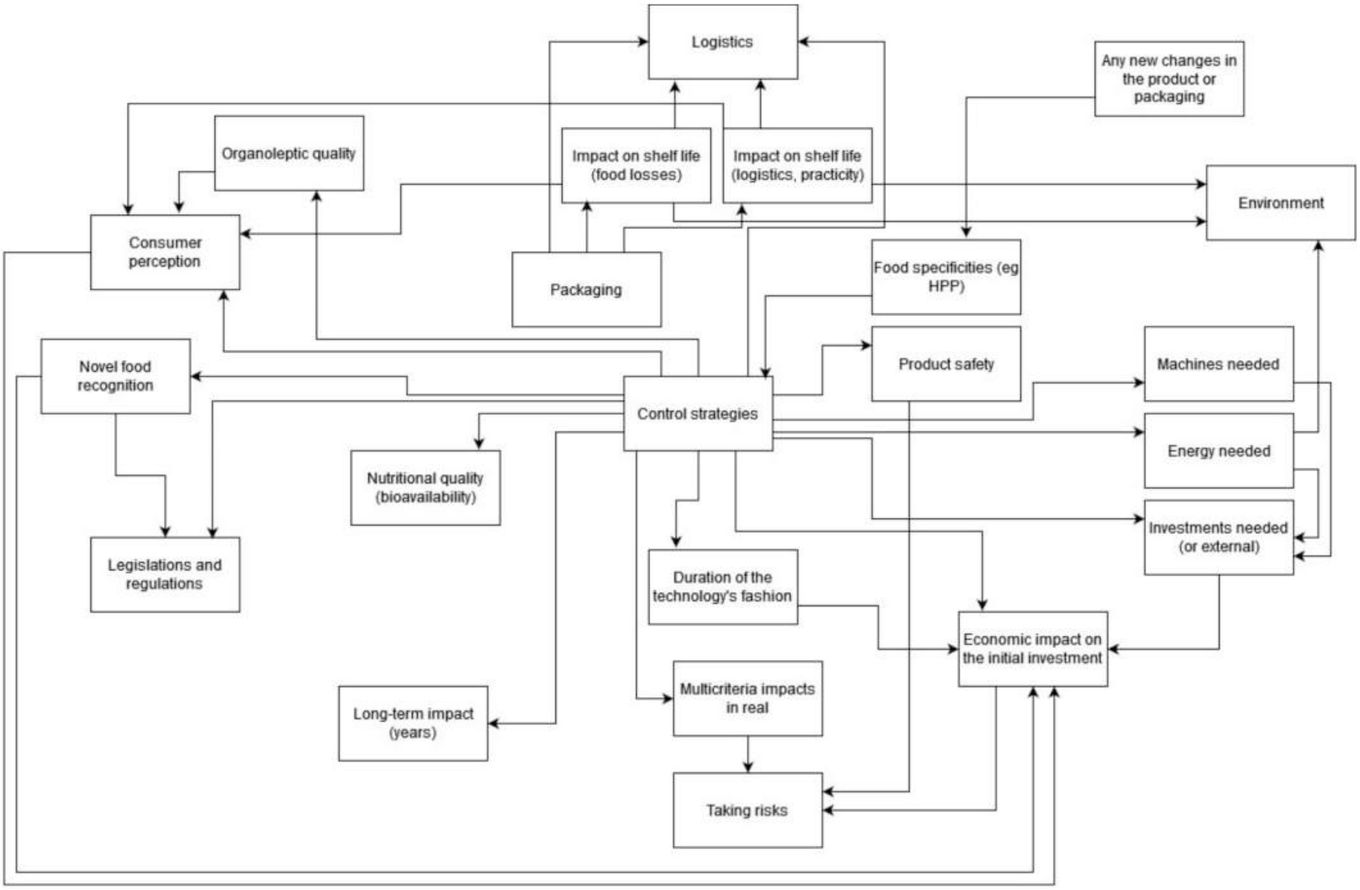

Fig. 2. Cognitive map built from the outputs of Working Group 2 "Hazard control and mitigation strategies". We suggest starting the reading of the figure from the middle concept "Control strategies", which influences the rest.

– For what reason?
– When (what date), etc.

- The computation of a "collective attitude" score, for each scenario. This score can be refined for a specific criterion or stakeholder. The notion of "collective attitude" proposed is a generalization, to a collectivity, of the notion of "attitude" defined in social psychology for an individual. This collective attitude is used in the SAFFI project to propose a global ranking of the five scenarios. It is computed as the weighted mean, on all criteria and aims, of the proportion of positive arguments. The weights are the numbers of arguments per aim. The result obtained for the collective attitude score is a real number between 0 and 1, where:
  – 0 and 1 are limits. These limits are thus never reached, which is technically allowed by initializing each aim with both a positive and a negative argument, transparent to the user. This property is important since it allows the score to continue and increase with the arrival of new positive arguments, even if only positive arguments are already present; and, inversely, to continue and decrease with the arrival of new arguments, even if only negative arguments are already present.
  – A score close to 1 expresses a collective attitude unfavorable to the scenario.
  – A score close to 0 expresses a collective attitude unfavorable to the scenario.
  – A score of 0.5 is neutral. The current situation (also denoted "business-as-usual" scenario), which is not described because it does not implement the new tools, corresponds by definition to the neutral score.

3. Results

3.1. Scenario building results

Cognitive maps built from the outcomes of the working groups

Figs. 1, 2 and 3 show the cognitive maps that were built for each of the three working groups, representing the concepts discussed and the interactions between them.

Grouping the concepts into more general variables

The concepts discussed in the working groups were merged into a limited number of more general variables. The variables obtained are listed in the first column of Table 1.

Influence and dependence of variables

Counting the incoming arrows into the concepts belonging to each variable, in the cognitive maps, the dependence of each variable was computed.

Counting the outgoing arrows from the concepts belonging to each variable, in the cognitive maps, the influence of each variable was computed.

The results obtained are shown in Table 1.

Key variables

The graph of Fig. 4 displays the positions of the variables according to their influences (in X axis) and dependences (in Y axis). The green vertical and horizontal lines correspond to the mean values of influence (mean value 10.18) and dependence (mean value 9.82) on all variables.

The variables situated in the top right part of this graph are defined as the key variables of the system. Both their influences and their dependences are above the average. This particularity states them as sensitive to changes from the variables upstream – due to their high dependence – and likely to provoke changes in the variables

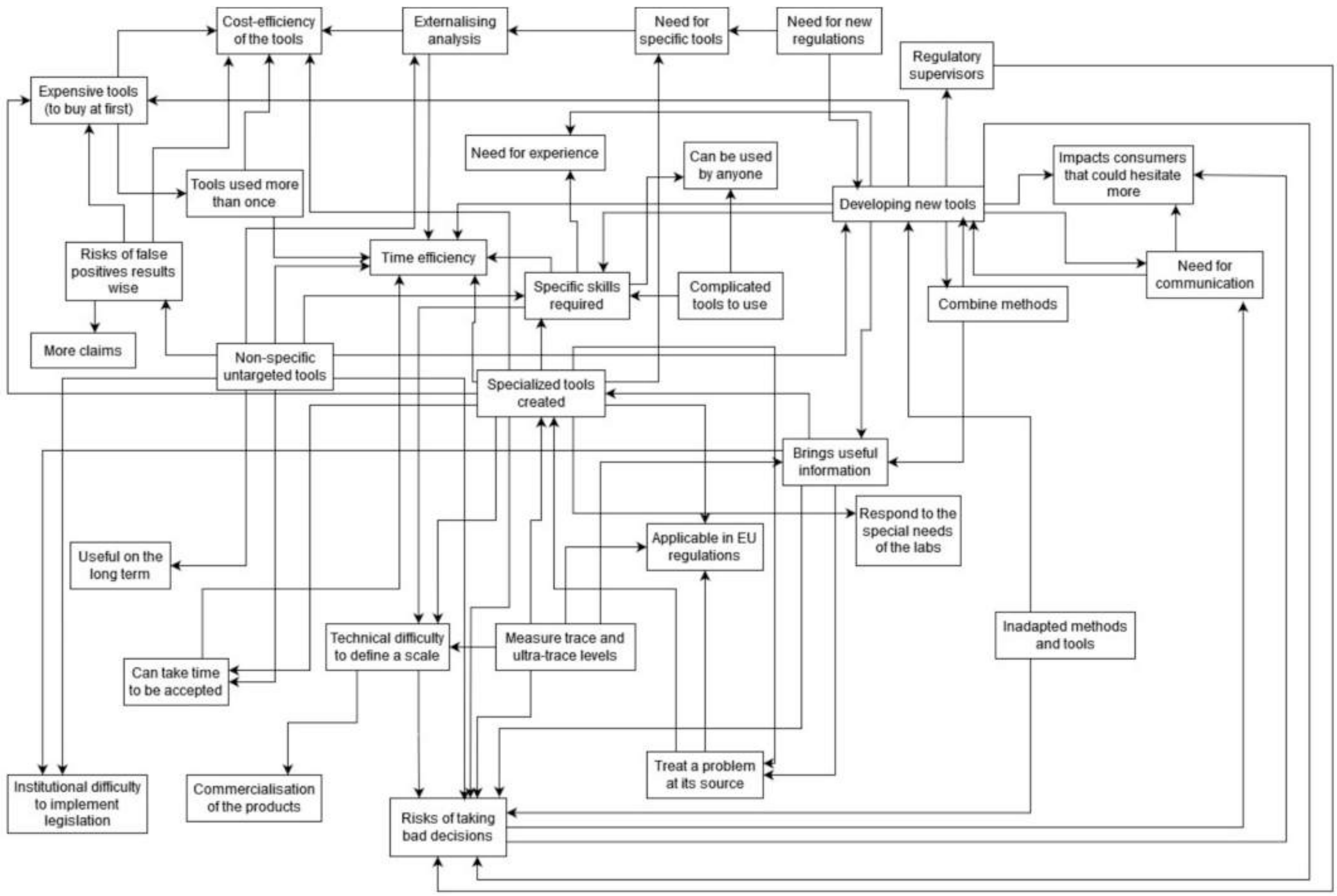

Fig. 3. Cognitive map built from the outputs of Working Group 3 “Hazard detection technologies”. We suggest starting the reading of the figure from concepts “Inadapted methods and tools” on the bottom right, and “Measure trace and ultra-trace levels” on the bottom middle.

Table 1
Variables, influences and dependences.

Variable		Influence	Dependence
A	Control strategies	18	2
B	Safety	1	5
C	Commercialisation	0	2
D	Type of tools developed	46	14
E	Economic	16	28
F	Product design	5	2
G	Energy	2	1
I	Informational	16	16
L	Logistics	0	4
M	Management	12	21
N	Environmental	3	5
O	Communication	2	5
P	Social outputs	0	4
Q	Product quality	4	4
R	Regulatory / Institutional	14	14
S	Social inputs	8	14
T	Technological	26	26

downstream – due to their high influence. They can be seen as unstable points of the system. For this reason, the combinations of the possible values of the key variables are used to build the scenarios.

Table 2 summarizes the six key variables obtained and the possible values of these key variables that will be considered in the rest of the method.

The scenarios

The combination of the possible values of key variables leads to 64 (i.e. 2^6) possible scenarios. Five of them were selected, based on the following criteria:

- **Interest for the SAFFI project**. Although one of the five scenarios developed (scenario 3) considers the case where new tools are developed with the same efficiency as before (value T2 of variable T), and with an equivalent level of global safety management (value M2 of variable M), most of the scenarios consider the situation actually studied in the SAFFI project. This orientates the choice of scenarios towards values T1 and M1, for variables T and M respectively.
- **The scenarios are credible**. This constitutes one of the step of the scenario method, in which only the combinations of values of the key variables deemed plausible by the participants are retained. For example, the combination of values E1 (expensive tools), T2 (same efficiency) and M1 (better problem solving) seemed irrelevant to consider.
- **The scenarios are contrasted**. To this end, all variable values are considered, with a relative equilibrium in their occurrences. For example, 3 scenarios consider targeted tools (value D1 of variable D) and 2 scenarios consider untargeted tools (value D2 of variable D); 2 scenarios consider expensive tools (value E1 of variable E) and 2 scenarios consider inexpensive tools (value E2 of variable E); etc.

Tables 3–7 describe the five scenarios, starting from the closest to the current situation ones, until the most exploratory ones.

3.2. Benefit-risk analysis results

Analysis of the scenarios per criterion

Fig. 5 depicts the repartition of positive/negative arguments

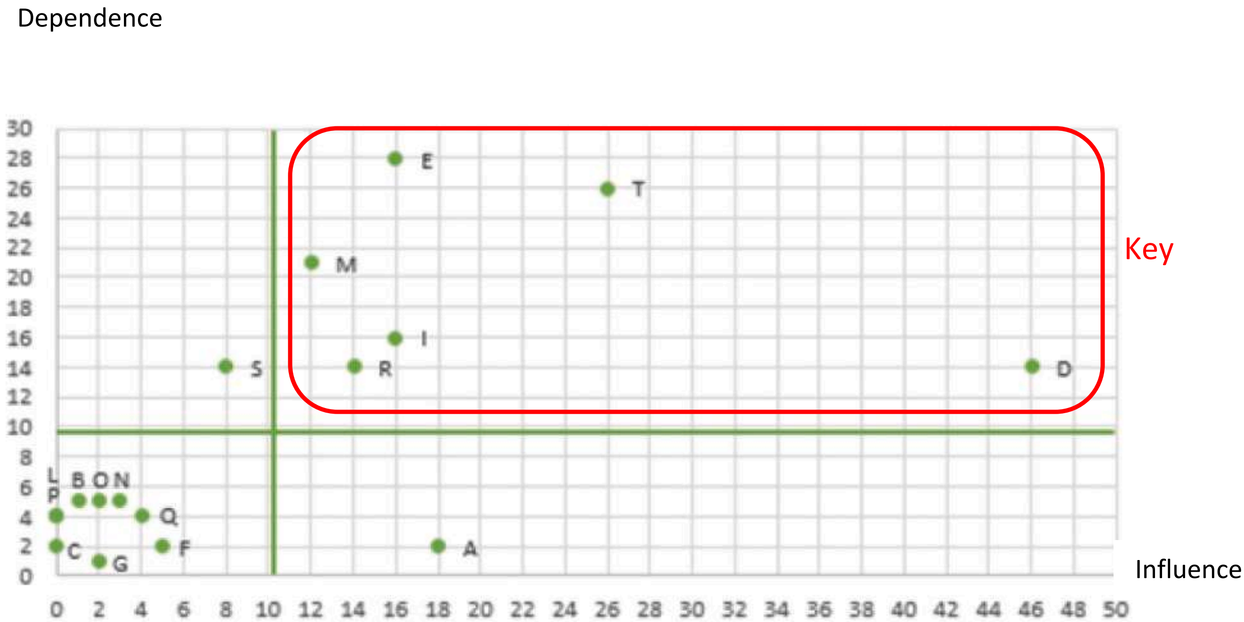

Fig. 4. Positions of variables according to their influences and dependences.

Table 2
Key variables and their values.

Key variables		Values	
D	Type of tools developed	D1	Targeted tools
		D2	Untargeted tools
E	Economic	E1	Expensive tools
		E2	Inexpensive tools
I	Informational	I1	Open access
		I2	Restricted access to information
M	Management	M1	Better problem solving
		M2	Unimproved problem solving
R	Regulatory / Institutional	R1	Adapted legislation
		R2	Non adapted legislation
T	Technological	T1	High precision and efficiency of tools
		T2	Same efficiency of tools

between the criteria, and the collective attitude per criterion, for each scenario:

Table 8 summarizes the main outcomes, while detailed explanations are provided hereafter for each scenario and for each criterion studied.

Scenario 1

Scenario 1 is favorable to:

- **Technological** advances: New efficient hazard detection tools are developed, but also control and mitigation technologies and more generally innovations in food processing. Obtaining appropriate organoleptic properties, using new soft-processing control and mitigation strategies, is noted as an uncertain point.
- **Social** advances: These are related, both, to the development of new skills and employments, and to the availability of new high-quality food products – with the exception of prices, possibly.

Table 3
Scenario 1.

Title: Two-speed economy
Specificities

- Availability (optional use) of new targeted, efficient but expensive tools, without public incentives.
- This scenario is mainly described from the point of view of risk monitoring and management.

	Variable		Value in this scenario
D	Type of tools developed	D1	Targeted tools
E	Economic	E1	Expensive tools
I	Informational	I2	Restricted access to information
M	Management	M1	Better problem solving
R	Regulatory / Institutional	R2	Non adapted legislation
T	Technical	T1	High precision and efficiency of tools

Description

New targeted (D1) high performance (T1) but expensive (E1) tools are available on the market. The regulations do not impose their use, since the safety constraints remain unchanged (R2). Specialized laboratories and most dynamic food industries are equipping themselves on their own initiative. Indeed, these new tools open up access to some new markets that are very demanding in terms of safety standards; they also allow them to build up substantial and reliable databases of their analysis history, thanks to new high-throughput analyses. These industries are experiencing a revival of innovation, for which new routine tools and analysis data make it possible to easily check whether a R&D innovation remains within safety standards, notably for chemical hazards. Data acquisition and model development in relation with research centers offers them better knowledge of their products and production environment; this knowledge is useful for identifying the origin of the problem in the event of an anomaly, notably at the microbiological level, and increases their agility with regard to regulatory changes (e.g. reduction of salt, nitrite contents, etc.). The analysis data remain private (I2) and the sector is moving towards a two-speed economy. The new tools allow the development of a few companies specializing in the construction and maintenance of new tools and in certain IT professions. Public authorities can partly rely, for safety monitoring plans, on the routinization of self-controls by large food industries. On average, safety management is experiencing some improvement (M1) which hides very large disparities. The changes are transparent to consumers.

Table 4
Scenario 2.

Title: Untargeted tools for research
Specificities

– Availability of new efficient but expensive untargeted tools, with generalization of open data.
– This scenario is mainly described from an academic research perspective.

	Variable		Value in this scenario
D	Type of tools developed	D2	Untargeted tools
E	Economic	E1	Expensive tools
I	Informational	I1	Open access
M	Management	M1	Better problem solving
R	Regulatory / Institutional	R2	Non adapted legislation
T	Technical	T1	High precision and efficiency of tools

Description
New untargeted (D2) high performance (T1) tools are developed. Thanks to advances made in research, they are more reliable – generating fewer false positives/false negatives – and make it possible to suspect the presence in foods of undetermined, emerging or re-emerging microbiological or chemical hazards under the effect of climate change, of process changes, etc. These new tools are expensive (E1). Their development has no short-term consequences on safety regulations (R2). For research laboratories and safety authorities, these new untargeted tools open the way to the discovery of new unknown or unsuspected contaminants: indeed, untargeted tests, if they prove positive without confirmation by targeted tests, can be at the origin of the discovery of unknown hazards. They are a springboard for the advancement of knowledge, multiplied by the generalization of open data in research (I1), and for the development of new targeted tools. Safety management is progressing over the long term (M1).

Table 5
Scenario 3.

Title: Small structure-inclusive
Specificities

– Availability of new low-cost tools, with equal performance, without public incentives.
– This scenario is mainly described from the perspective of small companies.

	Variable		Value in this scenario
D	Type of tools developed	D1	Targeted tools
E	Economic	E2	Inexpensive tools
I	Informational	I2	Restricted access to information
M	Management	M2	Unimproved problem solving
R	Regulatory / Institutional	R2	Non adapted legislation
T	Technical	T2	Same efficiency of tools

Description
New targeted tools (D1) as efficient (T2) but much less expensive (E2) than the previous generation tools, are available on the market. The regulations do not impose their use, since the safety constraints remain unchanged (R2). SMEs in the food sector, which are not yet equipped, and until now had their analyses carried out by service providers, find there the opportunity to equip themselves. Indeed, these new tools facilitate the development of new products, allowing the SMEs to more easily check whether an innovation remains within safety standards, notably for chemical hazards, while saving them service costs. They also allow them to build up databases of their analysis history. Data acquisition and model development in relation with research centers offers them better knowledge of their production environment and products; this knowledge is useful for identifying the origin of the problem in the event of an anomaly, notably at the microbiological level, and increases their agility with regard to regulatory changes (e.g. reduction of salt, nitrite contents, etc.). The analysis data remain private (I2) but their use is becoming more widespread. The new tools allow the development of a few companies specializing in their construction and maintenance. All replacements of existing equipment are now in favor of the new, less expensive tools. Public authorities can partly rely, for safety monitoring plans, on the routinization of self-controls. Overall, safety management remains stable (M2) but the disparities between companies are reducing. The changes are first transparent to consumers. Subsequently, as the price of tools continues to decline downwards, and these tools become more and more integrated into a single press-button device, civil society begins to take an interest in them: children care establishments, consumer groups, etc. Domestic practices, but also the distribution of responsibilities in terms of safety, are questioned.

– **Informational** advances: To a lesser extent, a progress can be noted in terms of data acquisition, model development, and better knowledge of the products and production environment, for the stakeholders that have the capacity to acquire the new expensive tools. However, data remain private and hence the advances inaccessible to small companies or civil society.

Scenario 1 is mitigated for:

– **Regulatory** aspects: On the one hand, since regulations remain unchanged, there is no legal recognition of the new advances, and novel foods remain unregulated. On the other hand, no new regulatory constraints are imposed to companies and any change involving the use of the new tools remains optional.
– **Safety** aspects: Although global food safety is improved, due to large-scale companies which control the larger part of market products, the safety level is heterogeneous and small companies are left behind regarding safety management.

Scenario 1 is unfavorable to:

– **Economic** aspects: Risk-taking is high for the companies that invest in the new detection tools and in new processing technologies. Indeed, the new detection tools are expensive, and the new processing technologies require important initial investments, with an uncertain long-term impact. Positive aspects concern the access to new high-safety demanding markets, enhanced innovation, and a return on investment expected.
– **Environmental** aspects: These are mainly mentioned regarding the new soft-processing technologies. Although reduced processing energy is expected, several other points remain unknown; for instance, energy during shelf life could be increased in case the new product are refrigerated, food waste could be increased if shelf life is reduced…
– **Logistics** aspects: Little developed, adaptation to new logistics seems a difficulty in this scenario – as in all scenarios where new tools, new equipment, new skills, new food products are expected.

Table 6
Scenario 4.

Title: Incentives to technical, digital and regulatory advances
Specificities

- Mandatory use of new efficient and inexpensive targeted tools, with strong incentive to share data.
- This scenario can be seen as an "ideal" scenario, all the optimal conditions (incentives from public authorities, efficient, inexpensive tools, openness of data, etc.) being met.
- Certain initiatives implemented in the past on certain hazards (e.g. in France, SCA food chain surveillance platform, DONAVOL safety self-monitoring data platform, etc.) can be considered close to this scenario.

	Variable		**Value in this scenario**
D	Type of tools developed	D1	Targeted tools
E	Economic	E2	Inexpensive tools
I	Informational	I1	Open access
M	Management	M1	Better problem solving
R	Regulatory / Institutional	R1	Adapted legislation
T	Technical	T1	High precision and efficiency of tools

Description
New targeted (D1), high performance (T1) and inexpensive (E2) tools are developed. The regulations are adapted (R1), setting new, more demanding safety constraints. These new measures reassure consumers about certain contaminants that were causing concern. To benefit from the large volume of self-monitoring data produced by companies thanks to the new tools, public authorities are setting up a centralized online platform, making detailed public analysis results available and regularly updated (I1), as well as incentives for the publication of anonymized private data on this platform. The new situation is beneficial for manufacturers of new tools and for certain IT professions. For safety authorities, it provides a volume of data allowing unrivaled knowledge of the safety situation in the sector. For all food industries, it opens up the possibility of negotiating access to some new markets that are very demanding in terms of health standards. Public authorities communicate to the general public about the excellence of safety guarantees and propose active participation of households in the online platform. The latter have the opportunity to describe in detail how they prepare the child's meals. The sector is experiencing a strong revival of innovation, particularly in soft processing technologies (e.g. HPP, etc.) reconciling safety control, nutritional benefit and reduced ecological impact, since the new routine tools and analysis data make it possible to easily check whether a R&D innovation remains within safety standards. Consumers, who are informed, are receptive to the new products, which limits risk-taking for the food industries. For safety authorities, the collection of regular information on domestic practices, combined with the performance of the new tools for the detection of hazards that can be generated at home (such as "process-induced" contaminants), makes it possible to better understand what is actually ingested by the child. Families can follow the latest recommendations. Safety management takes a leap forward (M1).

Table 7
Scenario 5.

Title: Democratization of untargeted tools – in the same way as targeted tools
Specificities

- Mandatory use of new efficient and inexpensive untargeted tools, with incentives for data sharing.
- This scenario is probably the furthest from current reality. However, since large private research laboratories are already interested in non-targeted tools, this scenario is presented as an exploratory one, to open discussions on possibilities in a more distant future.

	Variable		**Value in this scenario**
D	Type of tools developed	D2	Untargeted tools
E	Economic	E2	Inexpensive tools
I	Informational	I1	Open access
M	Management	M1	Better problem solving
R	Regulatory / Institutional	R1	Adapted legislation
T	Technical	T1	High precision and efficiency of tools

Description
New high performance (T1) untargeted (D2) tools are developed. Thanks to the progress made in research, these very reliable tools – generating few false positives/false negatives – and available on the market at affordable prices (E2), are revolutionizing safety monitoring. They make it possible to detect the presence in foods of undetermined microbiological or chemical hazards, emerging or re-emerging under the effect of climate change, of process changes, etc. The regulations are adapted (R1), setting new safety constraints that integrate the use of the new tools. These new measures reassure consumers about the safety of industrial products, while raising new questions. To benefit from the large volume of self-monitoring data produced by companies thanks to the new tools, public authorities are setting up a centralized online platform, making available detailed public results of targeted and untargeted analysis, updated regularly (I1), as well as incentives for the publication of anonymized private data on this platform. Huge volumes of data are available. Their exploitation is very complex. This opens the way to the development of new high-performance models from AI, however hardly interpretable by human operators. The new situation is beneficial for manufacturers of new tools and for certain IT professions. For the food industries, it opens access to new high-end quality labels that benefit from consumer confidence. For research laboratories and safety authorities, the new untargeted tools open the way to the discovery of new unknown or unsuspected contaminants: indeed, untargeted tests, if they prove positive without confirmation by targeted tests, can lead to the discovery of unknown hazards. They are a springboard for the advancement of knowledge and the development of new targeted tools. Overall, safety management is making strong progress (M1).

Scenario 2

Scenario 2 is academic research-oriented.

Its strong points are:

- High **technological** progress, with important advances in the efficiency of untargeted tools.
- A new insight into food **safety**, with proactive safety management and discovery of unknown or unsuspected hazards.
- Shared **information**, due to open access which allows all stakeholders to be informed of research data and knowledge.
- The absence of new **regulatory** constraints.
- The possibility to anticipate the effects of **environmental** changes (climate change in particular) on emerging or re-emerging hazards.
- **Social** awareness due to open access, and new skills due to technological progresses.

Its weak points are:

- The **expensiveness** of the tools.
- Limited **information** on private production environments, products and possible anomalies, since the new tools are dedicated to the research sector.

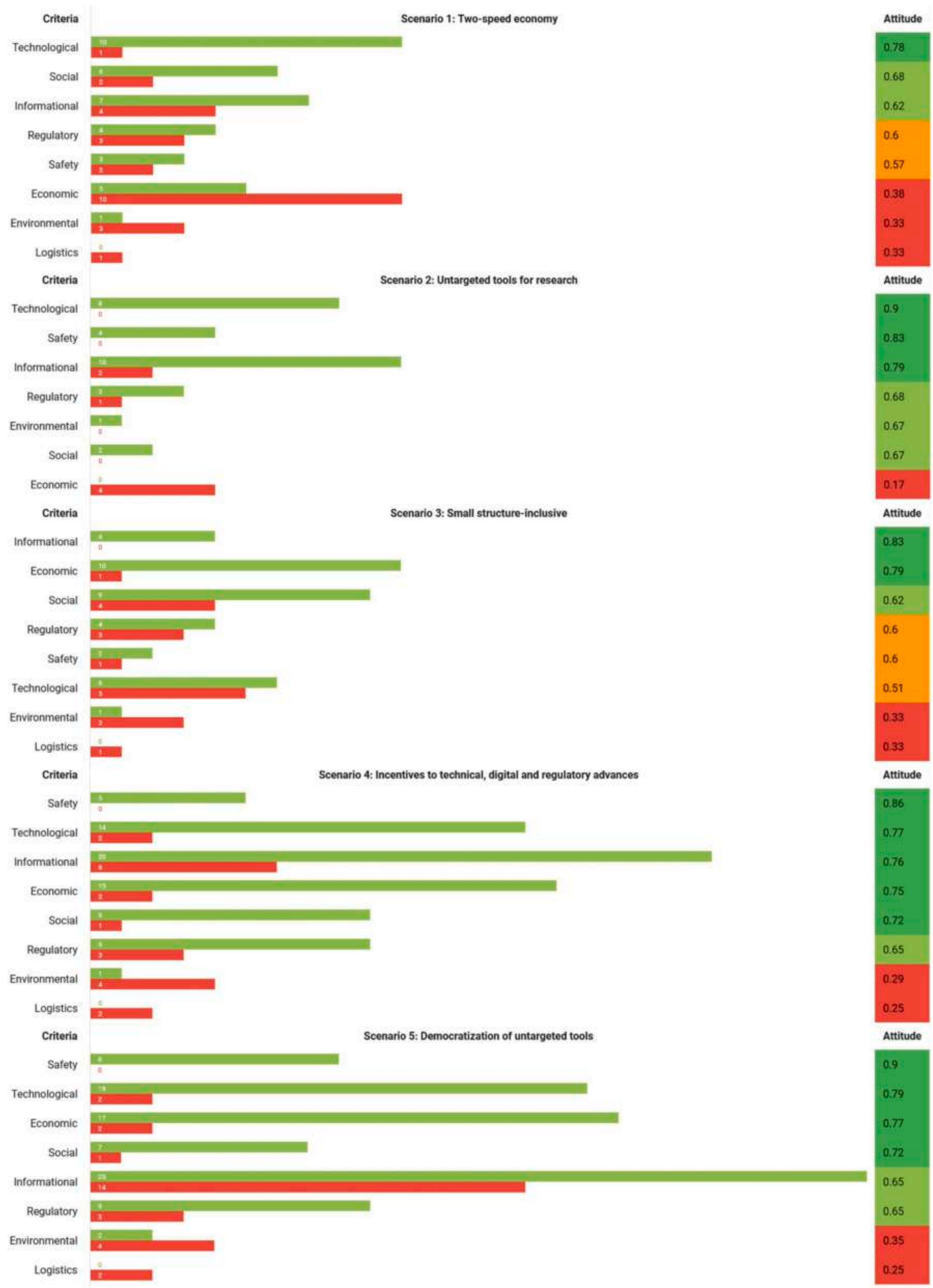

Fig. 5. Repartition of positive/negative arguments between the criteria and collective attitude for each criterion in Scenarios 1 to 5.
On the left side, bars representing the amounts of positive (in green) and negative (in red) arguments obtained for each of the criteria: Technological, Social, Informational, Regulatory, Safety, Economic, Environmental, and Logistics.
On the right side, the collective attitude computed for each criterion. The colour code indicates whether the scenario is considered very favorable (dark green), favorable (light green), close to neutrality (orange), or unfavorable (red) to this criterion. The criteria are ranked from the most favorable one to the most unfavorable one. This is why their order varies from one scenario to another. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 8
Summary of the main outcomes for each scenario and for each criterion of the study.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Technological	Favorable: New advanced tools	Favorable: Advanced untargeted tools	Mitigated: Enhanced for SMEs, no efficiency gain	Favorable: Multiple technological advances	Favorable: Advanced untargeted tools
Social	Favorable: New skills and jobs, High-quality food products	Favorable: Social awareness	Favorable: Increased civil society involvement	Favorable: New skills and jobs, High-quality products, Increased citizen involvement	Favorable: New skills and jobs, quality products, but limited access to citizens
Informational	Favorable: Progress in data and models	Favorable: Open public research data –but few on private environments	Favorable: Equal level of information for all structures	Favorable: Generalized progress in data and models (but effort in sharing information)	Favorable: Progress in AI models (but huge data complexity)
Regulatory	Mitigated: No regulatory constraints, yet no legal recognition of progress either	Favorable: No regulatory constraints regarding the new tools	Mitigated: No regulatory constraints, yet no legal recognition of progress either	Favorable: Legal recognition of safety advances	Favorable: Legal recognition of safety advances
Safety	Mitigated: Heterogeneous safety level	Favorable: Proactive safety management	Mitigated: Homogeneous but globally unchanged	Favorable: Improved and homogeneous safety level	Favorable: Proactive safety management
Economic	Unfavorable: High risk-taking for companies	Unfavorable: Expensive tools	Favorable: Accessible tools	Favorable: Access to tools, innovation and new markets	Favorable: Possible new labels
Environmental	Unfavorable: Ill-known and possibly increased environmental impact	Favorable: Anticipated environment changes	Unfavorable: Ill-known and possibly increased environmental impact	Unfavorable: Impact of digital transition, possibly increased impact	Unfavorable: Impact of digital transition
Logistics	Unfavorable: Adaptation needed	Ill-known	Unfavorable: Adaptation needed	Unfavorable: Adaptation needed	Unfavorable: Adaptation needed

- The absence of **regulatory** improvements.

Scenario 3

Scenario 3 has the specificity to introduce new targeted tools with the same efficiency as the previous generation ones, but much cheaper.

Its strong points are:

- Access to the same level of **information** regarding production environments, products and possible anomalies, for all structures, regardless of their size.
- **Economic** access to the new tools, to new high-safety demanding markets, to enhanced innovation, for small structures.
- Possible **civil society** participation and increased responsibility in safety management.

Its weak points are:

- Environment and logistics, for the same reasons as in Scenario 1.

Scenario 3 is mitigated for:

- **Regulatory** aspects, for the same reasons as in Scenario 1.
- **Safety** management, which gains in homogeneity due to the upgrade of small companies, but with an unchanged global level.
- **Technological** developments, which are enhanced on many fronts for small structures (new detection tools, but also control and mitigation technologies and more generally innovations in food processing), however with no gain in efficiency for the detection tools.

Scenario 4

Scenario 4 combines optimal variable values (efficient and inexpensive tools, openness of data, etc.).

Its strong points are:

- Improved global **safety** level, homogeneous regardless of the company size, with a gain in autonomy for companies.
- **Technological** developments, which are enhanced for all structures on many fronts (new detection tools, but also control and mitigation technologies and more generally innovations in food processing).
- **Informational** progress: The generalization of open access leads to data acquisition, model development, and better knowledge of the products and production environment, for all stakeholders.
- **Economic** access to the new tools, to new high-safety demanding markets, to enhanced innovation, for small structures.
- **Social** advances related to the development of new skills and employments, and to the availability of new high-quality food products. Possible civil society participation and increased responsibility in safety management.
- Contrary to the previous scenarios, safety **regulations** are updated (legal recognition of safety advances, regulation of novel foods). The digital transition is publicly funded through incentive measures.

Its weak points are:

- Sharing **information**, with good data quality, is an effort for all stakeholders, and especially for companies that share private data.
- New **regulatory** constraints are imposed to companies.
- Adaptation to new **logistics**.
- The digital transition is **environment**-unfriendly (the rest of environment-related discussions are common with Scenario 1).

Scenario 5

Scenario 5 is initialized with the same values of key variables as Scenario 4, except for the type of tools, which are untargeted here (versus targeted in Scenario 4).

The differences obtained are:

Strong points:

- A new insight into food **safety**, with proactive safety management and discovery of unknown or unsuspected hazards.
- **Technological** progress in untargeted tools, which can also lead to the development of targeted tools on the longer term.
- **Economic** possibilities: new types of high-end quality labels.

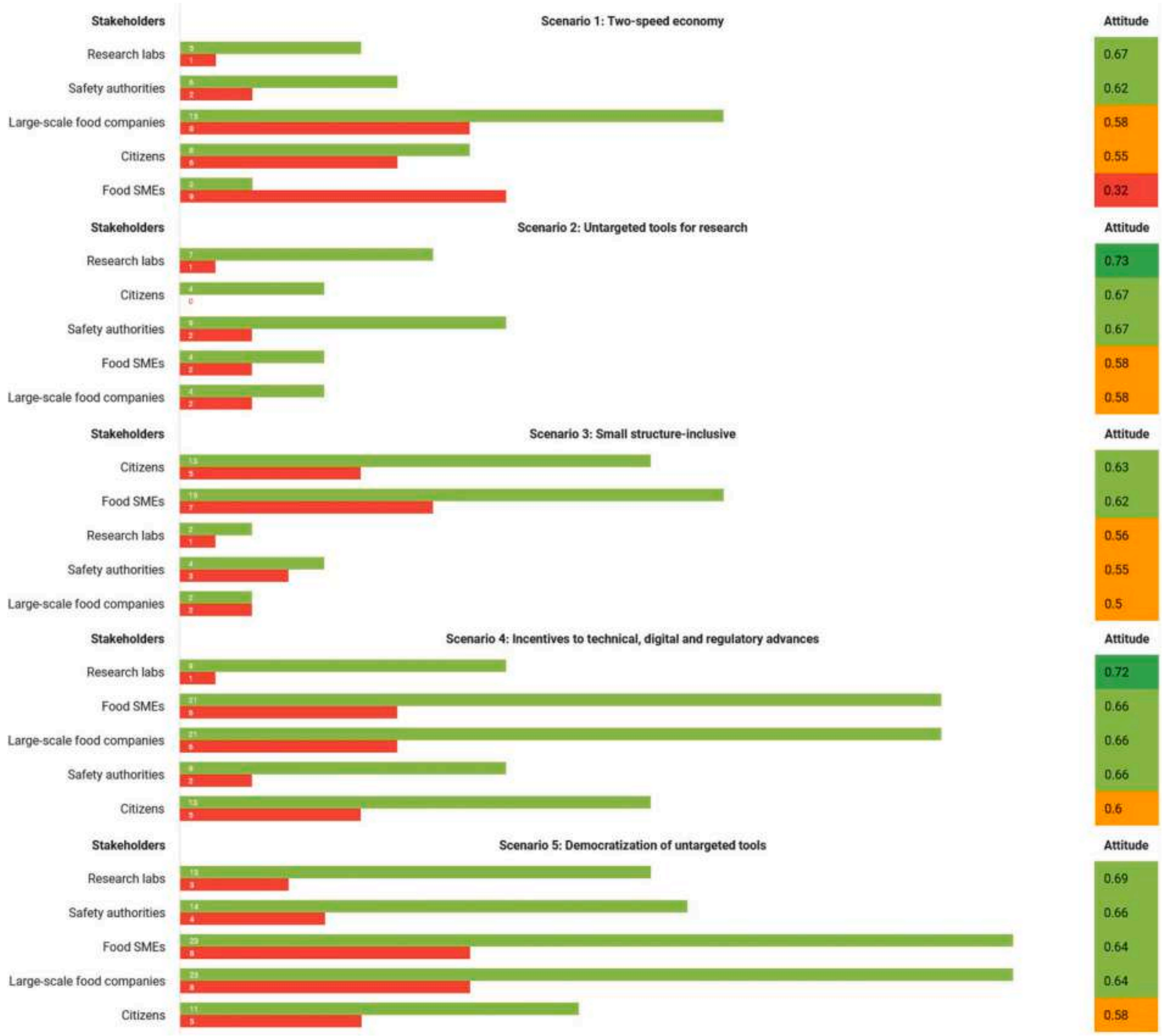

Fig. 6. Repartition of positive/negative arguments between the stakeholders and collective attitude for each stakeholder in Scenarios 1 to 5.
On the left side, bars representing the amounts of positive (in green) and negative (in red) arguments obtained for each stakeholder: Research labs, Safety authorities, Large-scale food companies, Citizens, SMEs.
On the right side, the collective attitude computed for each stakeholder. The colour code indicates whether the scenario is considered very favorable (dark green), favorable (light green), close to neutrality (orange), or unfavorable (red) to this stakeholder. The stakeholders are ranked from the most favorable one to the most unfavorable one. This is why their order varies from one scenario to another. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- **Informational** progress: development of new AI-oriented approaches to analyze the data.
- The possibility to anticipate the effects of **environmental** changes (climate change, modified food process or food product, etc.) on emerging or re-emerging hazards.

Weak points:

- **Informational** complexity: huge volumes of data generated and high complexity of the models to exploit them, with limited interpretability by human operators.
- Fewer possibilities for **civil society** involvement due to the complexity of the tools.

Analysis of the scenarios per stakeholder

Fig. 6 depicts the repartition of positive/negative arguments between the stakeholders, and the collective attitude per stakeholder, for each scenario.

Table 9 summarizes the main impacts on stakeholders in each scenario.

Global ranking of the scenarios

Fig. 7 shows an extract of the *MyChoice* user interface, with the list of scenarios on the top of the screen, and the corresponding collective attitudes on the bottom of the screen (part of the arguments are displayed in the middle for the economic criterion).

The scenario ranking is directly deduced from the collective attitudes associated with scenarios. Table 10 summarizes the collective attitudes and the ranking obtained.

Scenario 4, which groups favorable values of key variables with a focus on targeted tools, is ranked first, followed by the equivalent scenario with untargeted tools. Scenarios 2 and 3 come next, with equivalent attitudes, since their impact concerns a part of the stakeholders and is globally more restricted. Scenario 1 that leads to a two-speed economy due to expensive tools, comes last.

Table 9
Impacts of each scenario on stakeholders.

	Impacts on stakeholders
Scenario 1	This scenario is favorable to the structures that have access to the tools: research labs, safety authorities, and large-scale food companies. For the latter, the advantage is mitigated by risk-taking due to the high level of investment. The scenario is unfavorable to food SMEs which are left behind in terms of safety management and innovation capacity. Citizens benefit from the scenario on food quality aspects and skill/ employment development, with possible regression on product price, environmental aspects and awareness of the safety situation.
Scenario 2	This scenario is academic research-oriented and thus particularly favorable to the research labs which develop research approaches related to the new tools. Citizens and safety authorities also benefit from the scenario, especially through the proactive safety management allowed by untargeted tools with the discovery of emerging or re-emerging hazards. The scenario is neutral for food companies, which have access to the research results but no regulatory constraints.
Scenario 3	This scenario is favorable to small food companies that get access to a technology that they could not afford until now. It is also favorable to citizens with the possible development of participation, partnerships and more responsible involvement in safety management. It has limited impact on the other stakeholders, although some positive points (inexpensive equipment replacement for all stakeholders) and some negative ones (possibility of increased claims towards food companies) can be noted.
Scenario 4	This "optimal" scenario is favorable to all stakeholders, especially research labs which are not constrained by the implementation of new safety regulations. Companies benefit from many advances, yet they have to face data sharing. The benefit is also more nuanced for citizens, for two reasons (that also apply in other scenarios): the environmental impact of the new system which remains ill-known, and possibly increase product prices.
Scenario 5	This scenario, similar to the previous one but with untargeted tools, is globally favorable to all stakeholders. One aspect somewhat limits its benefits: the complexity of information and of data exploitation, which impacts all structures and makes the involvement of civil society more difficult.

4. Discussion

Interestingly, although the study focuses on the infant food sector—characterized by a highly vulnerable population, heightened scrutiny from stakeholders, and typically higher standards of safety and communication—it is notable that these sector-specific features were not among the key variables that emerged from the analysis. This observation suggests that the major challenges in developing new safety management systems are not primarily shaped by the nature of the food sector itself, but rather by more universal drivers such as the properties of the safety tools (e.g., cost, efficiency) and the broader institutional context (e.g., regulatory frameworks, incentive structures).

However, these specificities are not entirely absent from the analysis. While they do not define the key variables, they are reflected in secondary variables and the logic of the scenarios—particularly in how stakeholders accept risk-taking, implied by innovation, under currently stable safety conditions. The cognitive map of Fig. 2, in particular, expresses how control strategies (in the middle of the figure) influence, on the one hand, product safety and involve taking risks (at the bottom of the figure), and on the other hand, consumer perception (on the left side of the figure). In the cognitive map of Fig. 3, impacts on consumers that could hesitate more, and the need for communication, are mentioned as consequences of developing new tools (right side of the figure). In such contexts, the sensitivity associated with the infant food chain may influence the level of risk aversion and the prioritization of control

Table 10
Collective attitudes and scenario ranking.

Rank	Scenario name	Scenario collective attitude
1	Scenario 4 – Incentives to technical, digital and regulatory advances	0.74
2	Scenario 5 – Democratization of untargeted tools	0.69
3	Scenario 3 – Small structure-inclusive	0.63
	Scenario 2 – Untargeted tools for research	0.62
5	Scenario1 – Two-speed economy	0.57

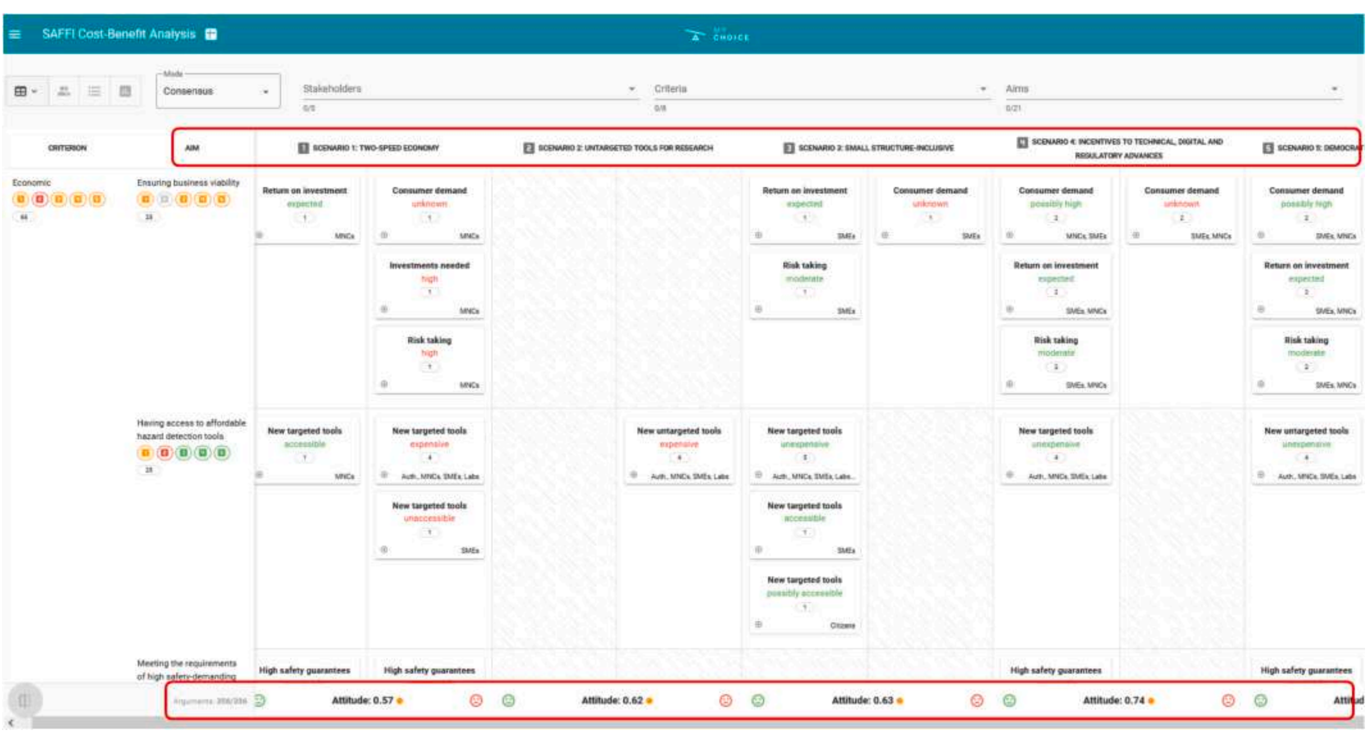

Fig. 7. Interface of the MyChoice tool showing the list of scenarios on the top of the screen, and the corresponding collective attitudes on the bottom of the screen.

measures.

In this study, "safety" refers to the broader objective of preventing adverse health outcomes, including microbial and chemical risks, not limited to regulatory compliance. While the current approach is qualitative and exploratory, it can be extended towards a quantitative framework, as demonstrated in previous work (e.g., Hachem et al., 2025). Such quantification would involve setting assumptions about the performance of emerging tools, their affordability, sampling protocols, etc. However, this added precision would inherently carry higher uncertainty, given the hypothetical nature of tool implementation at this stage. For instance, in Hachem et al. (2025), a probabilistic approach with simulated date is used. Our chosen approach focuses instead on general scenarios, aiming to uncover the systemic mechanisms that influence the adoption and effectiveness of new food safety strategies. This systemic perspective is intended as a complementary layer to quantitative risk-benefit analyses, particularly in contexts where safety innovation is still under development.

The focus in the present study is primarily on processing actors and downstream stakeholders. This choice reflects the scope of the SAFFI project, which centers on the means, for industrial processing steps, to control and mitigate safety hazards. Typically, some of these hazards even arise from industrial processes, such as the formation of thermally induced compounds like furan (Sandjong Sayon et al., 2024a, b). Thus primary producers such as farmers, fishermen, and animal breeders are not specifically included among the stakeholder groups. Nevertheless, the involvement of primary producers could be relevant for different types of safety hazards, such as those linked to agricultural practices, environmental contaminants, or primary production inputs.

5. Conclusion

This paper has explored the potential impacts of new hazard detection, control, and mitigation tools within the infant food chain, utilizing scenario building and benefit-risk analysis methodologies to assess prospective futures. The analysis demonstrates that while the implementation of these tools could significantly enhance food safety, their effectiveness depends heavily on key variables such as cost, efficiency, and accessibility. By considering multiple stakeholder perspectives, including those of regulatory bodies, food industries, and research organizations, the paper offers a nuanced understanding of the trade-offs involved in adopting these innovative solutions. Ultimately, the findings underscore the importance of a balanced approach, where technological advancements in food safety are aligned with economic and regulatory considerations. The global ranking of scenarios provided serves as a useful guide for decision-makers seeking to improve food safety practices while mitigating potential risks and costs. Further research and dialogue are necessary to refine these tools and ensure their successful integration into the food supply chain, particularly for sensitive products like infant food.

Major highlights from the scenarios studied are summarized as follows:

- Most positive impact is obtained when incentive measures are provided by public authorities, combined with several favorable conditions gathered: affordable tool price, updated regulations, and open access.
- The positive impact applies both for targeted and untargeted tools. For untargeted tools, the expected additional benefits –proactive safety management with discovery of (re)emerging hazards– are compensated by informational complexity –huge volumes of data, high complexity and limited interpretability of the models to exploit them.
- Tools price can turn the scenario around: from a boosted economy and improved safety in the case of affordable tools, to a two-speed economy with heterogeneous safety management in the case of expensive tools.
- The particular case of low-cost tools with unchanged efficiency is beneficial to small structures and to the participation of civil society in safety management.
- In all scenarios, the development of hazard detection tools is tightly linked to economic dynamics, by providing agility with regard to any change made in the product or process (whether it is due to regulatory changes, to innovation, etc.).
- Informational progress is double-edged. While improving the level of knowledge of product safety and production environment, the development of large volumes of data and models have their drawbacks: environmental impact of digitalization, model complexity, and effort for sharing private data and for producing well-documented data.

CRediT authorship contribution statement

Rallou Thomopoulos: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Romy Lynn Chaib:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Gaud Dervilly:** Writing – review & editing, Validation, Investigation, Conceptualization.

Declaration of competing interest

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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Data availability

Data will be made available on request.

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