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Not just noise monitoring: rethinking citizen sensing for risk-related problem-solving

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Can grassroots-driven citizen sensing initiatives triggered by distrust contribute to risk problem-solving? The article inspects such a potential in the field of risks to public health represented by noise pollution. After a conceptual reflection, the Amsterdam Schiphol and the London Heathrow airports' noise monitoring cases are compared. We inquire: How did lay people use citizen sensing to find solutions to the increase in noise? Which perceptions/actions influence and facilitate the problem-solving potential of citizen sensing? We found that the main citizens' actions leading to solutions are an adequate contesting of information monopoly through the production of valid data, as well as the challenging of institutional strategies to improve risk-related problem-solving. Accordingly, the citizen sensing initiative may generate mutual understanding and stimulate the institutional recognition of the problem and urgency for solving it. The article provides a novel exploration of evidence on performance of actors showing the problem-solving potential of citizen sensing through a preliminary performance matrix.

Keywords: Citizen sensing; risk problem-solving; environmental health risk; noise pollution; airports

1. Introduction: the increasingly sensing citizens

We investigate grassroots-driven monitoring activities, identified as practices of "citizen sensing", and their potential for risk-related problem-solving. For "grassroots-driven" we refer to initiatives launched by citizens, in contrast with institutional interventions powered by competent authorities. We opted for "grassroots" and "institutional" over the more popular dichotomy "bottom-up" vs. "top-down" (see e.g. Hai-Ying *et al.* 2014, 11) with the aim to capture a more blurred reality of social interactions. Although we describe citizen sensing broadly, the focus is on the monitoring of environmental risks that affect public health, specifically associated with noise pollution. Citizen sensing has received a considerable boost in recent years, thanks to the progress of monitoring technologies (Conrad and Hilchey 2011; Boulos, Resch, and Crowley 2011). While validity and reliability of grassroots-produced data tend to

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remain a problem (Gabrys 2016), recent technological developments and professional techniques have enabled citizens to perform *quasi-accurate* measuring (Corburn 2005; Dehnen-Schmutz *et al.* 2016). Overall, we register a growing trend of valuing citizens' input and perspective, especially when it comes to addressing uncertain risks (Bijker, Bal, and Hendriks 2009, 161) such as the noise issue discussed here. In the growing literature on citizen science and sensing, we find a focus on the learning and awareness side of the practice (Becker *et al.* 2013; Bonney *et al.* 2014). While the benefits for the citizens have been extensively researched (Den Broeder *et al.* 2017), only minor attention has been devoted to policy-related thinking. Along this line, Themba and Minkler (2003) researched the influence on policy-making of community-based participatory research. Also, the contribution that citizen sensing may bring to more accountable policy-making has been recently discussed specifically for the Schiphol noise case (Berti Suman 2018).

In this article, we go a step further by affirming that citizen sensing can be an effective tool for *problem-solving* of risks, besides creating awareness and accountability. Regarding problem-solving of risk we refer to complex, interacting networks in which choices and decisions are made around risks (Van Asselt and Renn 2011, 443) and solving is not only through the intervention of formal institutions and procedures, but also through informal arrangements, here exemplified by citizen sensing practices. The term risk problem-solving also has a normative meaning, standing for "a set of normative principles which can inform all relevant actors of society on how to deal *responsibly* with risks" [emphasis added] (Van Asselt and Renn 2011, 443). This normative argument forms part of the framework used in our analysis: the cooperation of all relevant actors (thus also including civil society members, such as the sensing citizens) is needed to achieve a *responsible* solving of a risk problem. Despite possible fragmentation, we acknowledge that institutional diversity brings the promise to actually improve the solving of risk problems (Kern and Bulkeley 2009; Bryson *et al.* 2013), by democratizing (risk) decision-making and achieving participatory solutions. However, which actors' performance influences the extent to which citizen sensing in practice can contribute to risk problem-solving has not yet been clarified.

The central questions underlying the analysis are: How did lay people living near airports use citizen sensing to find solutions to the increase in noise? What performance (perceptions/actions) drive and facilitate the problem-solving potential of citizen sensing? We distinguish between partial and full problem-solving, referring respectively to the achievement of a preliminary or complete solution to the risk problem. To answer the research questions, we built an analytical framework situated at the intersection of studies on participatory decision-making and co-production in public services and studies on progress in monitoring technology, by adopting an overall social capital approach (e.g. Putnam, Leonardi, and Nanetti 1993). The inquiry uses a case-study comparison between the Amsterdam Schiphol Airport (AMS) and the London Heathrow Airport's (LHA) systems for noise monitoring, both developed by civil society actors with a view to challenging institutional noise monitoring.

In Section 2, key concepts concerning citizen sensing are discussed and the outline of the analytical framework in the context of participatory policymaking is designed, followed by an analysis of adjacent concepts. Next, Section 3 presents the analysis of the two case studies, including a comparison, whereas Section 4 investigates the problem-solving potential of citizen sensing in the two case studies, using the analytical framework and performance matrix for assessing the cases' outcomes. The article concludes with implications of the results and future research paths.

2. Conceptualization

2.1. Defining citizen sensing

The concept of citizen sensing contains two elements, the citizen and the sensing. Citizen sensing, however, is just a currently popular buzzword, indicating manifold practices of grassroots-monitoring, which leads to a different use of the term between various actors. The actors of the sensing are *the citizens*, considered as lay people. Lay people in this article are understood as citizens acting in a non-professional role. *The expert* group is here composed of professionals and policymakers who rely on professional knowledge to shape their decisions and who are being confronted with citizen sensing practices.

Citizens engage in citizen sensing, motivated by a risk that they perceive as urgent. This sense of being at risk triggers a need to access first-hand data on the problem, entering a field traditionally dominated by experts. The gaining of such (noise) data creates a democratic outcome inasmuch as more actors become able to judge the soundness of experts' decisions. A characterization of the citizen side of the practice is provided by Gabrys with regard to air pollution citizen sensing associated with hydraulic fracking. The author suggests that "citizen sensing practices […] are […] ways of expressing care about environments, communities and individual, and public health" (Gabrys 2017, 175). The grassroots-driven, spontaneous nature, as well as the connection with the technology element, is also captured by Gabrys, who affirms that citizen sensing practices have emerged where people are taking up low-cost and DIY (Do It Yourself) monitoring technologies in order to gain a more immediate sense of their environmental conditions (Gabrys 2017, 182). In addition, Jiang *et al.* (2016, 2) provide a timely conceptualization of the grassroots-driven approach as a co-created, community-based, participatory research model where citizens are involved in all steps of the project.

The term citizen sensing originally referred to volunteered geographic information (Goodchild 2007), which currently appears too narrow. Burke *et al.* (2006, 4) identified the components that enabled citizen sensing to develop, including ubiquitous mobile phones and integrated web services, core network services and an application framework that simultaneously protects privacy and encourages participation. An updated definition is provided by Gabrys, Pritchard, and Barratt (2016, 3) who discuss the evolution of citizen sensing from being limited to the bottom-up production of geographic information to a wider set of participatory, DIY and digital sensing practices proliferating through advanced sensor technologies. More recently, the practice was framed in the Citizen Sensing Toolkit (Making Sense 2018, 7) as a form of citizen participation in environmental monitoring and action which is bottom-up, participatory and empowering to the community.

On the sensing component, Boulos *et al.* (2011, 6) stress the importance of the detection of a physical presence and the conversion of that data into a signal that can be read by an observer, provided that accuracy in measurement is guaranteed (Autsen 2015; Jovašević-Stojanović *et al.* 2015; Jiang *et al.* 2016). However, the sensing citizens would perform a measurement with an additional value, as they also engage in information sharing, fusion and analysis, thereby shifting from mere information gathering to information analysis for problem-solving (Srivastava, Abdelzaher, and Szymanski 2012). This additional role is also emphasized by Goodchild (2007, 218) who views the sensing citizens as intelligent interpreters of local information with a role to play in solving the sensed problem, and by Becker *et al.* (2013, 1) who emphasize the cross-fertilization process entailed in participatory sensing.

2.2. Citizen sensing in the context of democratization and co-production

The citizen sensing initiatives here studied are analysed through a framework built on three intersecting dimensions: (1) the democratization of power entailed in a shift to a participatory problem-solving; (2) co-production in public services (here interpreted broadly as also including institutional risk monitoring) and (3) progress in monitoring technology which supports both processes. Starting from the first dimension, citizen sensing fits into a broader trend of decentralization of some public tasks or services (Ostrom 1990) to citizens, also indicated as public participation, which tends to accelerate today (Holtmann and Rademacher 2016). Such a trend resembles experiences of participatory problem-solving and co-production through the so-called (urban) living labs. Accordingly, citizens have the opportunity to shape new solutions to problems through collaborative learning with other stakeholders. Van Geenhuizen (2018a, 2018b) stresses the analogous potential of innovation in urban living labs in shaping user-centred solutions. Yet, living lab methodology is often applied when already a certain consensus does exist about the role of citizens. In addition, living labs are frequently designed by the institutional actors, thereby maintaining vertical decision-making (Michels and De Graaf 2010, 488). In contrast, practices of citizen sensing tending to problem-solving seek the overturning of such a vertical structure.

Key points of attention underlying the three dimensions of our framework include trust, legitimacy and inclusion (Bryson *et al.* 2013), concepts belonging to the broader social capital theory. Social capital theory focuses on those resources, for example, trust, norms and network connections, that are inherent in social relations and facilitate collective action and problem-solving, through bonding and bridging, eventually based on reciprocity (Coleman 1988; Jackman and Miller 1998; Putnam, Leonardi, and Nanetti 1993; Kusakabe 2012). Civic participation and engagement are thought to cultivate social capital (and the other way around), among others through leadership and organizational commitment to solve (risk) problems (Nabatchi and Amsler 2014). A positive interplay between civic engagement and social capital building inspired our case study analysis through paying attention to performance regarding trust/distrust between the citizens and the institutional actors responsible for managing the risk. Accordingly, the citizens living in the risk area share an *exclusive* experience that "bonds" and they *distrust* the institutional actors involved (2nd dimension). Eventually, citizens gain legitimacy to act by having the risk recognized among a broader public, in particular when the monitoring is acknowledged by institutional actors to be a valid sensing system (our 3rd dimension). Next, we investigate whether and how convergence can arise (1st dimension), a stage requiring the establishment of a *trusted* dialogue between the two parties which may ultimately lead to the institutional recognition and solving of the problem at issue through interventions by the authorities. A form of shared *risk-problem solving through trust* emerges. The co-production involved indicates activation of the 2nd dimension of our framework, and the overall convergence also entails a democratization of the whole problem-solving process, thus connecting with our 1st dimension. Reaching convergence, however, is highly dependent on the characteristics of the problem and the context in which the actions evolve. Performance in terms of trust/distrust and the changes involved are the basis for the preliminary performance matrix, in which assumed performance is compared with evidence provided by the case studies (see for an example of such a matrix, Emerson and Nabatchi 2015, 739).

Finally, in general, the following issue has to be mentioned: citizen involvement in policymaking could increase the *legitimacy* of the decisions adopted. Yet, recent findings disconfirm this argument – the reason why a nuance regarding the selection of participant citizens needs to be added. Participants would often be "the usual suspects", middle/rich class, well-educated, already politically knowledgeable and having a high sense of responsibility. This nuance may "undermine the legitimacy and democratic value of participation" (Michels and De Graaf 2017, 877–880). Selection of participants is also a major concern for citizen sensing, which faces the challenge of inclusion in order to ensure an appropriate range of (conflicting) interests in the process (Bryson *et al.* 2013). The cases' analysis will take these concerns into account, but first the various practices adjacent to citizen sensing have to be disentangled.

2.3. Citizen sensing and adjacent concepts

Citizen sensing is not an isolated practice. Rather, there are many adjacent and interrelated experiences, as illustrated in Table 1. We identified: community-based monitoring, citizen science, participatory (environmental) sensing, mobile crowdsensing, citizen observatories and participatory digital culture. In this section, these practices are compared by taking as reference their aims and orientation, origin of the initiative, selection of actors and the three dimensions indicated above: democratization of power, co-production with an institutional actor and focus on technical innovation (see Table 1). Various categorization efforts related to participatory forms of sensing have been performed in recent years (see Eitzel *et al.* 2017, for a study on citizen science terminology with emphasis on the different cultural nuances; Comber *et al.*, 2014, for a study on terms used to describe citizen sensing and crowdsourcing with emphasis on semantic differences). Our adoption of citizen sensing as a term of comparison of the practice against adjacent experiences is original. However, findings may vary depending on the selected starting point and the actors involved, causing terms to remain blurred, as Lewandowski *et al.* (2017) observed for the related concept of citizen science. The following is an attempt to categorize a blurred reality against an identified practice.

Practices of *community-based monitoring* have an emphasis on the direct involvement of community members in monitoring of local problems (Fernandez-Gimenez, Ballard, and Sturtevant 2008) often aimed at the preservation of natural resources and ecological quality, but with increased application in health services provision in developing countries (J-PAL Policy Briefcase 2015). Such practices would bring about a shared understanding among diverse participants and social capital building, thereby fostering social learning and adaptive management (Fernandez-Gimenez, Ballard, and Sturtevant 2008). These aspects are found also in citizen sensing. However, in our opinion, community-based monitoring tends to be stronger engaged with community-building and representation of the community (light 1st dimension), and on co-production of data (strong 2nd dimension), elements less emphasized in citizen sensing. Furthermore, such practices are often planned from institutional actors and then offered to the community. Finally, different from citizen sensing, the main trigger for the practice is often the scarcity of data on a problem (e.g. loss of nature) and the need to engage the community in its solving.

Table 1. Comparison of citizen sensing with adjacent concepts.

Initiative and major sources	**Citizen sensing** (Gabrys 2017; Jiang *et al.* 2016; Making Sense 2018)	Community-based monitoring (Fernandez-Gimenez, Ballard, and Sturtevant 2008; J-PAL Policy Briefcase 2015)	Citizen science (Den Broeder et al. 2017; Van Brussel and Huyse 2018; Cooper *et al.* 2017)	Participatory env. sensing (Kotovirta, Toivanen, R. Tergujeff, and Huttunen 2012; Turreira-García *et al.* 2018; Abbot and Guijt 1998)	Mobile crowd sensing (Ganti, Fan, and Hui 2011)	Citizen observatories (EC EASME website; WeObserve platform; Liu *et al.* 2014)	*Less adjacent:* Participatory digital culture (Karaganis 2007)
Key feature	Citizen-sensor interaction for tracking environmental risk	Monitoring performed by the community	Participation of lay people in science	Measurement of environmental phenomena (**location-based applications**)	Crowd of **sensing citizens**	Citizen-based Earth observation applications	Open source software production and social Internet applications
Primary aim and orientation	Producing citizen-sensed data to verify or challenge institutional data	Achieving community engagement and community-building	Supplementing scientific analysis, rebuilding **people's trust** in science	Mostly gathering of information in a cost-effective way	Sharing data to measure and map phenomena of **common interest**	Mostly enhancing the management of land and natural resources	Matching the production, distribution, and use of Internet services
Selection of sensing actors	Self-selection: citizens as laymen and as concerned people	Based on representation of the community and its needs	Mostly performed by institutional actors: the selected citizen-scientists	Often performed by institutional actors: local community (owning a location aware device)	Self-selection: individuals with **sensing** and computing **devices**	Often performed by institutional actors: local community engaged in an observatory project	Self-selection: potentially all users of the Internet
Origin of the initiative	Distrust; scarce transparency; information monopoly; emotional triggers related to risk	**The lack of data on a problem;** community involvement in data gathering	The need to **reduce the gap** between science and society	The need to gather large environmental measurements	The **concern over a collective problem**, need for a large number of data points	The need to perform in-depth observations over time	The wish to collectively benefit from advantages of the Internet
Degree of democratization of power (1st dimension)	High: in general **grassroots-driven, spontaneous**	Medium: institutionally driven, planned, but focus on community representation	Medium: often institutionally driven, planned	Low: mostly institutionally driven, planned	High: in general **grassroots-driven, spontaneous**	Medium: often institutionally driven, planned, recently EU-funded	High: **grassroots-driven, spontaneous**
Co-production with institutional actor (2nd dimension)	Eventually in next step	Strong	Strong	Weak	**Eventually in next step**	Medium	No
Focus on technological innovation (3rd dimension)	Medium	Low	**Medium**	High	High	High	**Medium**

Note: The text in bold corresponds to aspects of partial overlap/coincidence of adjacent fields with citizen sensing.

Citizen science instead stands for the active participation of lay people in scientific research (Den Broeder *et al.* 2017, 1). In its broader understanding, citizen science would be more targeted to scientific knowledge production (co-production, strong 2nd dimension), rather than policymaking. However, recently citizen science has been recognized as contributing both to science and to policymaking (Van Brussel and Huyse 2018). Kullenberg and Kasperowski (2016, 1) identify a strand of citizen science which particularly overlaps with citizen sensing, namely, that related to monitoring of health and the environment, like the iSPEX micro-dust particulates monitoring project (KNAW 2018). Many biodiversity-oriented citizen science initiatives may have a sensing component, such as monitoring bees (also) for the sake of human subsistence (Cooper *et al.* 2017). A clear distinguishing element is identified by Gabrys, Pritchard, and Barratt (2016, 3) in the sensor component. Citizen sensing, differently from citizen science (and from community-based monitoring), requires as a pre-condition the reliance on some form of sensor technology, for example, enabling production of audio maps. It is nonetheless true that citizen science may also rely on sensor technology.

We here consider citizen sensing as a possible sub-set of the broader domain of citizen science, the latter practice being generally more grassroots-driven, sensor-based and less focused on scientific contribution. In our opinion, citizen sensing and citizen science are increasingly converging, as citizen science is going beyond the mere data collection to support science and it is becoming a new methodology to validate science itself and to trigger "behaviour change [.] building social capital around environmental issues" (Van Brussel and Huyse 2018, 1). Eventually, citizen science practices can have an impact on policymaking (Hallow *et al.* 2015), similarly to what is argued here for citizen sensing. In addition, challenges are shared, such as representativeness and validity of the data (Freitag, Meyer, and Whiteman 2016; Van Brussel and Huyse 2018), and in terms of achieving "deep citizen engagement and policy influence" (Van Brussel and Huyse 2018, 1).

Another adjacent concept is that of *participatory sensing* applied to environmental monitoring. Kotovirta *et al.* (2012, 155) refer to the practice of people acting as mobile environmental sensors and users reporting their personal observations or measurements of particular environmental phenomena, such as air and water quality and spread of plant disease, using special location-based applications on their mobile phones (3rd dimension). In addition, participatory sensing can act as a complementary information source in institutional (environmental) monitoring. Participatory sensing can, indeed, be considered as a practice of participatory environmental monitoring (PEM), which refers to approaches involving local people in the structured gathering of information about the environment where they live (2nd dimension) (Turreira-García *et al.* 2018, 24, referring to Abbot and Guijt 1998). Yet, participation in these projects is often limited and mostly functional to the gathering of information in a cost-effective way. Nevertheless, a number of PEM initiatives are worth mentioning because of their application in monitoring noise, with a focus on representing "the real exposure experienced by the citizen" (Maisonneuve, Stevens, and Ochab 2010, 51). Other authors discuss noise participatory sensing as an alternative to standard techniques for environmental monitoring, as occurred, for example, in the NoiseTube project in Antwerp (D'Hondt, Stevens, and Jacobs 2013, 681). Guillaume *et al.* (2016) discuss PEM applied to noise as a potential source of noise data of high temporal and spatial granularities, as recommended by the European directive 2002/49/EC. Similar to citizen sensing, issues of data management and the need for quality assurance and standards for interoperability emerge.

A concept that often overlaps with citizen sensing is that of *mobile crowdsensing*, occurring when individuals through sensing and computing devices collectively share data and extract information to measure and map phenomena of common interest (strong 1st and 3rd dimensions) (Ganti, Fan, and Hui 2011, 32). We endorse the interchangeability of citizen sensing with mobile crowdsensing, though the latter concept has a stronger focus on the sensing component and on the benefits of having a *crowd* of data points, not necessarily composed of citizens worried about a risk, as in our two case studies.

Citizen observatories are yet another form of environmental monitoring performed by civil society actors, recently defined by the European Commission as community-based environmental monitoring and information systems which build on novel Earth observation applications embedded in portable or mobile personal devices. The WeObserve platform[1] defines them as community-based environmental monitoring and information systems that *invite* individuals to share observations, typically *via* mobile phone or the web. The focus here is on the observation, rather than actual engagement in problem-solving, and on the use of advanced digital Earth observation applications (strong 3rd dimension), also witnessed by Liu *et al.* (2014). A link to policy emerges (1st dimension) and, as the citizens are invited to co-produce observations, the 2nd dimension also seems emphasized. Recently, a number of EU-funded citizen observatories grew in Europe supporting the management of land and natural resources, such as Ground Truth 2.0 and LANDSENSE.[2]

Although less adjacent to citizen sensing, the concept of *participatory digital culture* is worth discussing. Karaganis (2007, 9) identifies the roots of such a culture in the combination of open source software production and social Internet applications such as Napster, Wikipedia and YouTube, which have created digital media communities with millions of participants (link to the 1st dimension) where the boundaries between production, distribution and consumption become blurred (link to co-production, but not with institutional actors). The described digital culture with its growing participatory dynamics may be considered the *ancestor* of the interplay between digital environments and participation, which gave rise to most practices discussed in the preceding lines.

After mapping of citizen sensing against adjacent practices and contextualizing the practice along three dimensions, we move attention to the analysis of the two case studies.

3. AMS and LHA

3.1. Methodology

The aim of analysing the AMS and the LHA noise monitoring cases is to understand the response of lay people to the risk represented by an alleged increase in noise disturbance and the potential of this response for addressing and solving the problem. In this context, we perceive the problem as consisting in the (perceived) scarce transparency and miscommunication in the institutional handling of the public health risk associated with high noise levels, induced by airport expansion. We conduct a case study analysis of two comparable cases in order to identify partially convergent development patterns aimed at problem-solving (Yin 2009) and to explore our theoretical ideas, which, in further research, may be tested to reach generalizable conclusions (Mayring 2007). Overall, the methodology has been shaped by a triangulation of different data sources and mixed methods, with the aim of grasping multifaceted dynamics and context-dependency. We summarize the different steps as follows. First, we conducted an exploratory search in the arena of noise citizen sensing to select relevant cases, the population of the study encompassing the set of citizen sensing projects tackling noise risk. In order to identify relevant projects, we combined literature search with web search on: the Scistarter platform,[3] a repository for citizen science initiatives; the Citizen Sense platform in the section "Projects"[4]; and the recent EC inventory (Bio Innovation Service 2018) detailing 500+ cases of citizen science for environmental policy. Next, two case studies, AMS and LHA, have been selected for the following reasons. Both cases are relevant for the international debate on noise governance, affecting two strategic transport hubs, while revolving around the controversy between public quiet and well-being *versus* economic interests linked to airport expansion. Moreover, in both cases, an easily accessible web platform was created gathering information about the project evolution. Finally, both cases particularly elucidate the problem-solving potential of citizen sensing. The cases differ in terms of time frame as AMS dates back to 2003, whereas LHA to 2009. In addition, information on the AMS case, especially from sources external to the initiative, was more abundant than information on the LHA case. The LHA case has probably been obscured by more successful noise participatory sensing experiences, such as the WideNoise App, also used in Heathrow (Becker *et al.* 2013).

Secondly, in-depth research into the two cases has been performed on material available in English and Dutch (the latter only for AMS), mainly as secondary data, including literature review of scientific publications discussing the cases; analysis of earlier social research (for the AMS case, our study partially drew on the work of Carton and Ache 2017); content analysis of mass communication messages, such as blog posts and newspaper articles, of the projects' websites, including observation of the respective noise maps and of documents produced by organizations related to the cases (such as reports from noise-competent authorities). We acknowledge that collecting data from websites' observations may have inserted bias into the analysis as the platforms are operated by the citizen sensing initiatives obviously striving to show success. However, we have also been engaged with various communications and feedback sessions on the subject (e.g. two expert interviews, respectively, with an expert on environmental health risk and an expert on citizen science at the Dutch National Institute for Public Health and the Environment – RIVM) as well as with participation in four thematic workshops[5] and two conferences.[6]

Third, we shaped the case-study analysis on the basis of the framework built on the theoretical notions outlined in Section 2.2, which figures a number of critical junctures, from a situation of perceived risk to potential actions contributing to risk problem-solving. In the two cases analysed, we indeed inspect to what extent the citizen sensing initiatives stimulated a more democratic decision-making, co-created solutions and triggered progress in noise monitoring. Inspired by theory of governance and participatory problem-solving (Bryson *et al.* 2013; Emerson and Nabatchi 2015; Ansell and Torfing 2016), in the case study analysis of performance of actors we use the term *perceptions* as a way of thinking/feeling about the risk problem and its management, and *actions* as those interventions concretely adopted by the sensing citizens but also responsible authorities. In addition, we use *enabling conditions*, referring to those contextual factors that support preparation of the scene for the problem-solving stage (as opposed to hindering).

3.2. The AMS noise monitoring case

Amsterdam Schiphol Airport is the main airport of The Netherlands and the third largest passenger airport in Europe,[7] situated close to densely populated areas. The citizen sensing initiative was launched as a response to the political decision to expand the airport by creating a fifth runway (the *Polderbaan*), officially opened in 2003 only for night flights, and from 2004 in full operation. In response to this expansion, environmental activists and parties filed numerous complaints against the project, in relation to the risk of an increase in noise burden for the residents. The Dutch Minister of Transport, Public Works and Water Management (currently part of the new Ministry of Infrastructure and the Environment), responsible for the expansion of the airport, on public media, reassured those groups that the expansion would not have affected the inhabitants' quiet (Carton and Ache 2017). As a consequence of the expansion, the inhabitants started reporting intrusive noise levels affecting their sleep and causing headache and other ailments (Carton and Ache 2017). The Ministry's response was that noise could not be measured due to interferences, such as wind direction, and to disturbances from the environment, but it could just be calculated using mathematical models.[8] As a reaction, the residents lamented the lack of transparency in how the public was informed about the noise burden, in particular in connection to an "information monopoly" arising from the denied possibility to measure noise, and from the fact that the measuring stations were owned by the Schiphol Group (Carton and Ache 2017, 246, 248). This situation stimulated the idea of alternative monitoring in the local community (the push for democratization, 1st dimension). Yet, as only a proportion of the residents measured noise, there may still be a legitimacy deficit.

Carton and Ache (2017) detail the rise of the initiative: Rene Post, a person trained in Information Communication Technology (an expert not acting in his professional role) decided to launch a citizen sensing initiative – although *not* qualified as such – aimed at obtaining meaningful evidence of noise impacts on the residents' quiet. A group of 25 local volunteers started measuring noise levels using 25 microphones, costing around 200 euro a piece (Carton and Ache 2017, 242). The microphones were placed on house roofs and their recordings were then sent to local personal computers (the network of sensing citizens), registered on a website (now converged into the "Sensornet"[9] platform) and stored on a central server, reflecting a push to innovation (3rd dimension). Access to the network allowed users to visualize, *via* graphics, the noise data (in their entirety or per individual microphone).

When the visualization of noise loads was made available through open access, the project attracted the interest of a broader public: 10 municipalities in the interested areas and a semi-public environmental organization joined the citizen initiative to create a professional foundation, "Geluidsnet".[10] The initial shortcomings of the Sensornet platform were tackled and the impact of the platform grew. The system, from a small-scale idea, developed to become a widely-used system for assessing noise country-wide, detailed by Carton and Ache (2017, 243–246) as a process of "institutionalization" of the instrument. In addition, the citizen initiative inspired other collectives of residents exposed to noise nuisance, which could make use of Geluidsnet's noise measurements. On the current website, various municipalities in

The Netherlands, governmental organizations (e.g. rail infrastructure), and even actors from abroad are listed as users. Geluidsnet provides not only a service for measuring noise from aircraft, but also from trams, shipping, car traffic and manufacturing industry. Although most of the clients of Geluidsnet are governmental organizations, the platform still provides easy access to citizens for sharing their noise measurements.

The scaling-up of the project demonstrates a key element: the grassroots-driven initiative eventually gains the attention of the institutional actors and a dialogue between the two parties begins. Interestingly enough, the initiative was positively received by Dutch municipalities and not by the national government (Carton and Ache 2017). However, concrete measures have recently been implemented by the Schiphol Group to reduce noise production, including the adoption of specific flying techniques (landing and taking off), whereas discussions are ongoing on allocating landing rights to quieter and cleaner aircraft (Lucht- en Ruimtevaart Nederland 2017). In addition, AMS intends to mitigate noise from departure (ground noise) through specific landscaping techniques (Schiphol 2018). Currently Geluidsnet and Schiphol's own online noise measurement system, NOMOS,[11] do not differ in terms of data output. The presence of two comparable platforms enables a cross-check of the noise information and shows that Schiphol lost the information monopoly on noise monitoring (Carton and Ache 2017, 246). In addition, as pointed out by the authors (Carton and Ache 2017, 246), the initiative achieved its central goal, which was to demonstrate that it is "difficult but not impossible to measure noise", contrary to what was initially defended by the national government. Accordingly, "the objective of open, independent, observed-and-measured, factual information about airplane noise was achieved" (Carton and Ache 2017, 242), which encouraged the institutional actors to create their own parallel noise measurement platforms. Carton and Ache (2017, 243) indeed argue that the official noise online mapping system, NOMOS, was created in 2005 based on the example set by Geluidsnet. The authors detail how the Alderstafel, an advisory body for the Dutch government on the development of Schiphol, even commissioned a study to compare the two systems (Carton and Ache, 2017, 243; Schiphol Alderstafel 2012).

The discussion on a proper appreciation of the citizens' input when noise is assessed seems particularly timely as an expansion is planned at Lelystad Airport, aimed at absorbing selectively part of Schiphol's growth. This expansion at a distance of 40 km to the east of Amsterdam raises civic concerns on adverse environmental and public health impacts and stimulated requests to carry out new noise calculations (using an updated method) which were satisfied by the national government (NRC-Handelsblad 2018), thereby suggesting an ongoing policy change. Despite this positive note, rather problematic developments have been observed close to Schiphol (Bewoners Omgeving Schiphol 2017). A new policy drawing on a shortage in regional housing would allow municipalities to build houses in areas where it is forbidden due to the close proximity to runways. Future buyers of these houses will have to sign a contract, attached to the house (in Dutch, *kettingbeding*), eventually banning them from complaining about noise annoyance deriving from airport growth.

3.3. The LHA noise monitoring case

LHA, as the busiest airport in Europe,[12] is surrounded by densely populated areas, and, therefore, represents an outstanding example of adverse impacts of noise on the environment and on human health.[13] The noise burden was allegedly addressed by the institutional actors through "a top-down approach with little public participation, but much public scepticism".[14] The contested approach is based on noise generation and sound propagation contour maps drafted exclusively by the government and airport authorities (specifically, using the Civil Aviation Authority's Airport Noise CONtour computer model), which fail to give account of the public concern surrounding the topic. The perception of being excluded from the controversial noise debate[15] made the affected inhabitants responsive to citizen sensing. The expansion was subsequently halted due to political and social opposition and a public consultation was held on the topic. On 25 June 2018, the majority of the House of Commons voted in favour of the third runway,[16] after the project had already obtained approval from most of the government.[17] The expansion works are planned to start in early 2021.[18] As a consequence, a judicial review of the decision was launched by four London boroughs impacted by the expansion, in partnership with Greenpeace and the London mayor.

The launcher of the citizen sensing initiative, as for the AMS case, is an individual expert in technology, Ian Tout, specialized in Geographical Information Science. In 2009, Mr. Tout started the LhrNOISEmap project[19] based on mobile phone technology capable of capturing noise levels, together with an infrastructure for collating, analysing and visualising this information, and aimed at using "mobile phones to develop a citizen driven model for the collection of noise data and the production of noise intensity maps"[20] (3rd dimension, technical progress). Mr. Tout acknowledged on the project website that the key factor for the success of the initiative lies in the "engagement with local communities […], both in the collection of data and the contribution of local knowledge and experience" (the 1st dimension, democratization of risk problem-solving).[21]

The project, similarly to other citizen sensing initiatives, comprises an app that allows users to feed data into an online open-access map. Any interested person can participate by simply downloading the free app from the Apple App Store. Consideration seems timely at this point: despite the aim of inclusiveness, the fact that the app can be run exclusively on iPhones makes it usable only by selected people, that is, owners of iPhones. Once the app has been downloaded and the user has setup an account, she/he can start recording. After the recording has been performed, the so-called "NoiseBoo" app enables participants to share noise information remotely gathered, similarly to the way in which YouTube users can with videos. The sample recorded can be uploaded on the AudioBoo map, provided that it is tagged as "lhrnoise". In addition, the user can add a description, on top of the user's location that it is automatically recorded. Additional information that facilitates the noise analysis is related to whether the aircraft is landing or taking off, the type of aircraft, the airline, the runway used, the type of phone being used. In the words of the project creator, "AudioBoo facilitates the creation of an audio map on which markers represent the location of a recording, which – once clicked – play a sample of aircraft pollution recorded at that location".[22] Overall, the initiative not only created an alternative system for noise data collection, but also an effective way to visualize noise on a map thanks to the audio recordings. Different to traditional noise meters that perform only noise level readings, audio recordings allow the user to create an interactive map where noise pollution can be *experienced* online.

The primary aim of the lhrNOISE map was to challenge authoritative noise contour maps. On the basis of a considerable number of noise samples, the initiative succeeded in visualizing noise in the form of a Noise Contour Layer,[23] similar to the map officially produced by Heathrow where users can track flight paths and related noise levels.[24] The success of the initiative emerges in this complementary map which, differently from official data, uses citizen-generated noise information, bringing the promise of helping the citizens to "better understand and communicate experiences of aircraft noise pollution".[25] On the lhrNOISE website, every interested individual can download excel data sheets to guide her/his own noise measurements. This open and inclusive approach suggests that the tool has the potential to be widely used. However, the information currently available on the case is not sufficient to assess how many people actually joined the initiative and whether any institutional actor made use of the tool; different from the AMS case that allowed such an assessment.

Nonetheless, on the institutional side, what can be interpreted as a response to the noise problem is the Fly Quiet and Green programme[26] developed by LHA with the aim of reducing noise pollution by encouraging quieter aircraft and flight methods, including the implementation of the "League Table" in charge of ranking airlines according to their noise performance,[27] the introduction of more predictable periods of noise respite for the residents, the reduction in aircraft waiting time and the limit to the use of running power units and to engine testing on the ground.[28] In addition, the official Heathrow platform[29] now provides a space to make a complaint about noise, a web page on making Heathrow quieter, and a "Heathrow Community Noise Forum".

It can be hypothesized that there is a relationship between the people's feeling of anger and distrust expressed in the citizen sensing initiative and the institutional response that shows a shift towards a more transparent and participatory handling of the noise problem. However, it cannot be confirmed that one is consequential on the other, being an acknowledged dimension of co-production missing in the case. In addition, a cross-reference analysis has shown that, different to the AMS case, the LhrNOISE map has not figured in institutional and academic discussions (except for a brief mention in Zimmerman and Robson 2011, 35). Yet, the airport's new sustainability strategy and official platform seem to value the creation of a trusted dialogue with the concerned citizens.

3.4. Comparing the two cases

The two cases present the following shared elements, which may shed light on citizen sensing's development patterns:

- The lack of an agreement – that is, institutional denial or disregard of the risk – on the existence, nature and extent of the noise problem, and the divergence between the interests of the affected groups (e.g. their quiet) and the interests of the policymakers (e.g. the airports' growth);
- The rise of the initiative as purely grassroots-driven, initiated by citizens rather than by appointed institutions (1st dimension, a push for democratization in risk problem-solving);
- The sensor devices and the sensor network aimed at sharing risk information on an open access platform, and the data visualization on interactive maps triggering public opinion beyond the citizen network and abroad. Also, the "good enough" quality and usefulness of the data for policymaking (both, 3rd dimension, technological progress);

- The institutional interest at a later stage towards the grassroots-driven initiative (emphasised more in the AMS case), which opens the way for a co-production of solutions to the noise risk problem, or at least to its monitoring (the 2nd dimension, co-production);
- The conceivable link to problem-solving (communicating more openly about the noise problem and mitigating it through specific interventions by the airport authorities), although in both cases the airport expansion has not been halted.

4. Discussing the noise problem-solving potential of citizen sensing

Before discussing the actual problem-solving potential of the two initiatives it must be said that its qualification depends on how the problem is defined. As indicated above, for this analysis, the problem coincides with the scarce transparency in the institutional handling of the noise-related risk for the affected inhabitants.

The case studies suggest that both ICT-based initiatives contributed to the achievement of an alternative, factual, open measurement of noise exposure in populated areas surrounding the airport (3rd dimension, technical progress). This can be viewed as a coping mechanism providing a citizen-driven solution to the handling of the noise problem, thus concretizing the 1st dimension of analysis. Yet, measuring does not mean already solving the problem; rather, it creates a trigger for the solving. The full solving is, instead, here identified *only* in causing institutional recognition of the problem and in stimulating the urgency for mitigating it through practical interventions, which corresponds to the co-production phase, the 2nd dimension. However, the contribution to the full problem-solving has been induced and shaped by a number of perceptions, actions and enabling conditions related to the initiatives, which relate to each other differently in terms of causal attribution. Such perceptions, actions and conditions can be understood by considering the complexity and diverse dynamics of the networks, including emphasis on emerging distrust, creation of trust, legitimacy and inclusion, towards the achievement of a trusted dialogue and the co-production of problem-solving strategies. All these dynamics resonate with social capital inspired theory on participatory policymaking (Renn, Klinke, and van Asselt 2011; Kusakabe 2012; Bryson *et al.* 2013).

In order to understand the actual contribution of each actor, either citizens or institutional actors, in the network, we classified their perceptions and actions according to their increasing influence on problem-solving (Ansell and Torfing 2016), as indicated in the preliminary performance matrix (Table 2). In the design of this matrix, we used four classes of increasing relevance: (1) initial conditions enabling problem-solving; (2) steps towards problem-solving; (3) partial problem-solving and (4) full problem-solving. We linked the classes to our analytical framework of performance in terms of trust/distrust and classified the observed perceptions/actions in the case studies accordingly, while adding labels on actor's origin as follows: the citizens (citizens label), related to problem-solving as an institutional response to citizen sensing (institutional label), and (partially) common or trust-based initiatives (both labels) (Table 2).

Under the first class, we identified evidence of perceptions operating as enabling conditions for problem-solving. Among such evidence we listed the perceived malfunctioning and dogmatic attitude of the institutional response to the risk problem, combined with the perceived inconsistencies in the institutional approach to the problem. Both these perceptions arose from the citizens' side. The mentioned conditions

Table 2. Preliminary performance matrix: problem-solving potential of citizen sensing in AMS and LHA cases.

Performance: stages [a]	Evidence: perceptions/actions [b]
Initial conditions enabling problem-solving [risk perception, multi-actor risk management, distrust] *Preparatory stages corresponding to "Origin of the initiative" in* Table 1	1. Perceived malfunctioning and dogmatic attitude of the institutional response to the risk problem (citizens) 2. Perceived inconsistencies in the institutional approach to the problem (citizens) [both 1st dimension]
Steps towards problem-solving [multi-actor problem-solving, positive social capital and mutual understanding and legitimacy] *Stages corresponding to "Co-production with institutional actor" and "Focus on technical innovation" in* Table 1	3. Creating a high quality citizen sensor system displaying the urgency of the problem (citizens) [3rd dimension] 4. Achieving data validity and reliability leading to the contesting of information monopoly (citizens) [3rd dimension]) 5. Drawing attention to the risk problem of own community and broader public (citizens) [3rd dimension] 6. Emphasizing the citizens' entitlement to be properly informed about risks (citizens) [1st dimension] 7. Building mutual understanding on a shared problem (citizens and institutions) [2nd dimension]
Partial problem-solving [problem-solving through civic engagement, participation and co-production (trusted dialogue), and social capital (integration of initiatives)] *Stages corresponding to "Primary aims and orientation", "Degree of democratization of power", and "Co-production" in* Table 1	8. Adequately challenging institutional strategies to improve institutional risk governance (citizens and institutions) [1st dimension] 9. Integrating the citizen initiative with institutional systems of governance and achieving a trusted dialogue by dropping dogmatic attitudes (citizens and institutions) [apparently only AMS] [2nd dimension]
Full problem solving [convergence, problem-solving through civic engagement, participation and co-production, and social capital] *Stage corresponding to "Primary aims", "Democratization of power" and "Co-production" in* Table 1	10. Recognition of the problem, the value of the citizens' contribution, and implementing practical interventions to mitigate or solve the problem (citizens and institutions) [1st and 2nd dimension]

Note [a]: text in brackets is "assumed performance", derived from specific theoretical perspectives.
[b]: the list of evidence on performance (perceptions/actions) is not necessarily a sequence.

triggered numerous steps that, in turn, led to the solving phase. Among them, we found, on the citizens' side, the creation of a citizen-sensor system producing valid results and displaying the urgency of the problem to the public; the achievement of data validity and reliability which facilitated the contesting of the information monopoly; the attraction of the own community's and the broader public attention to the risk problem (legitimacy); the emphasis on the citizens' entitlement to be properly informed about potential risks. From the citizens and the institutional levels, at this stage, we pinpointed the building of mutual understanding and agreement on a shared problem.

The presented steps activated the preparation for problem-solving phase, where we identified a series of actions both from the citizens and from the institutional actors, namely, the adequate challenging of institutional strategies to improve institutional handling of risk and to enhance its transparency, the integration of the citizen initiative with institutional systems of governance, and the achievement of a trusted dialogue to mitigate or solve the risk problem, facilitated by the dropping of dogmatic attitudes towards the problem by the institutional players. In particular, the verification that the action of the sensing citizens stimulated the dropping of dogmatic attitudes towards the way in which the problem was addressed seems a key stage for achieving problem-solving.

Furthermore, apparently only in the AMS case, the initiative achieved integration with the institutional system for measuring noise, at least at the municipal level. Indeed, the citizens could offer their sensing system to the institutional stakeholders and engage in a trusted dialogue with them, which seems an essential element of the successful harmonization of citizen sensing into the institutional problem-solving process. As such an institutional integration only occurred in the AMS case, it is worth wondering what might explain this difference. To this aim, it should be noted that the citizen initiative Geluidsnet, which later became Sensornet, *pre-existed* the official Schiphol noise measurement system. Differently, the LHA citizen sensing initiative was developed when an official noise system was already in place. The *filling of institutional gaps* seems to have played a key role in facilitating, or even determining, the institutional uptake of the citizen intervention. The institutionalization of the AMS initiative suggests that citizen initiatives may converge into the institutional frameworks of risk problem-solving, and thus the two approaches can be complementary.

Finally, and under full problem-solving, the nodal contribution we identified from citizen sensing to the AMS and LHA controversies is represented by the creation of the institutional recognition of the problem and of the urgency for solving it through practical interventions. In both cases, the appointed institutions made steps to improve risk communication and the transparency of the official noise measuring systems. Factually, we observed that both airports have recently taken measures to reduce or mitigate noise, for example by introducing new flying techniques, by enhancing the use of quieter aircraft, and by reducing ground noise through specific landscaping. Although not necessarily directly *caused* by citizen sensing, these developments may have been *encouraged* by the initiatives launched by the concerned citizens.

Yet, all these measures do not limit air traffic. Consequently, we may hypothesize that, when there is still room for mitigation or prevention of noise annoyance, citizens may have a say in problem-solving and citizen sensing may indeed work. Different, however, when it comes to more drastic decisions, such as a halt to airport growth, as the issue then becomes more complicated and room for the people's input may be more limited. Thus, the magnitude and comprehensiveness of the problem and of possible solutions may determine the extent of citizens' involvement in problem-solving.

Some reservation needs to be made when reading our analysis and the underlying Table 2. Both show a simplification of assumed causal relations. Interventions may reinforce each other while working simultaneously. Such patterns of causality are disregarded; moreover, a specific order of interventions is suggested, which is an oversimplification, as initiatives overlap and multiply at a pace that cannot be captured accurately in written form. Furthermore, we had to disregard various external conditions to those presented here and in the table, which may have intervened and contributed to determine a specific outcome.

5. Conclusion

Using relevant literature and analysis of two case studies, we concluded that citizen sensing can stimulate the solving of a given problem, both preparing the ground for problem-solving, partially solving it, and stimulating full problem-solving. Under the full problem-solving, the key contribution we identified from citizen sensing is the creation of institutional recognition of the problem and of the urgency for solving it through practical interventions aimed at mitigating the risk. Accordingly, we observed that both AMS and LHA airports have adopted measures aimed at enhancing transparency and reducing noise. Such measures may be seen as encouraged by the citizen sensing initiatives. Although we could not prove causality between citizen sensing and problem-solving, we defended the plausibility of such a relationship, especially in the AMS case, as acknowledged in the literature (Carton and Ache 2017). Overall, we identified a push from the citizen towards a more open, transparent and responsible handling of the noise problem, which recalls the normative aspect stressed by Van Asselt and Renn (2011).

Affirming that citizen sensing can contribute to problem-solving and thus improve risk problem-solving under certain conditions has serious implications in that it challenges opinions supporting a more closed management of risks. The collection of alternative and competing data may undermine the authority of the institutions responsible for the problem. Furthermore, the reliance on alternative data sources could cause more chaos than clarity and substantially delay the problem-solving process (De Jong and Boelens 2014). However, if citizens' input is included *before* conflict arises, the need for evidence checking *ex-post* would likely disappear and the relationship between people and institutions could arguably improve. Another critique may be raised in connection with the existence of different risk perceptions influencing individual opinions on correct risk problem-solving (Renn and Klinke 2016). False information or perception biases (Renn and Klinke 2016, 1) could undermine the validity of the laymen knowledge on the problem. When integrating citizen sensing within institutional risk handling it is thus necessary to take into account the major psychological and social mechanisms of (risk) perception (Renn and Klinke 2016, 1).

This study faces various shortcomings, which are partially substantial and partially methodological. Given practical constraints, interviews with participants and spectators of the two initiatives have been lacking. Future research could be enriched with this data source. In addition, a future research agenda should include the inner motivations that push citizens to engage with citizen sensing: What causes them to address the risk and become active in the sensing? To what extent is there a general level of dissatisfaction/distrust that reinforces the perception of problems and triggers action? In addition, to what extent are the sensing citizens representative of the population that is facing the risk?

Another limitation is the difficulty in picturing the actual amount of participants that joined and currently participate in the two initiatives and the numbers of sensors actually deployed, as these data are not clearly stated on the projects' platforms (in particular for LHA). A deeper search should target this information gap. In addition, as the two noise monitoring systems rely on different devices (low-cost microphones and smartphones) the kind of participation and access barriers may substantially differ, eventually implying an unbalanced engagement and numbers of citizens in the two projects, which should be inspected in future research. Furthermore, the measurement of aircraft noise with low-cost sensors and smartphones, in both cases, could be susceptible to measurement bias, which should be considered when advocating for citizen sensing's uptake by institutional actors.

Moreover, in dealing with ever-evolving initiatives, we could not provide an exhaustive overview of the two noise monitoring platforms. Future attention may focus on how the noise maps evolve over time in conjunction with the planned airport expansions. Also, a future search on causal patterns should consider an extended scenario of (external) events possibly influencing the problem-solving outcome and providing a stronger base for further development of the performance matrix. By designing a causal model and building a large database of citizen sensing projects the current qualitative study could be extended with quantitative analysis and provide more clarity on influences that enhance or inhibit problem-solving.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes

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2. See, respectively, http://gt20.eu/ and https://landsense.eu/. Accessed November 10, 2018.
3. See https://scistarter.com/. Accessed November 9, 2018.
4. See https://citizensense.net/projects/. Accessed November 9, 2018.
5. Lorentz Center workshop on "Multilateral Governance of Technological Risks", 22–24 May 2017, Leiden, The Netherlands; workshop on "Citizen Science – Gamma Radiation, Noise Annoyance and Air Quality" at the Ministerie van Infrastructuur en Milieu, November 14, 2017, Utrecht, The Netherlands; workshop on "(Un)taming Citizen Science" at KU Leuven, December 4, 2017, Leuven, Belgium; Citizen Science COST Action workshop on "Citizen Science and Environmental Monitoring: Benefits and Challenges", November 21–22, 2018, Ispra, JRC.
6. Annual NILG Forum 2017 on "Technocratic Law and Governance" at The Netherlands Institute for Law and Governance, November 30, 2017, Amsterdam, The Netherlands; Conference "Unpacking the 'Accountability Paradox' in Expert-Based Decision-Making" at the Erasmus School of Law, Erasmus University of Rotterdam, December 1, 2017, Rotterdam, The Netherlands.
7. See http://ec.europa.eu/eurostat/statistics-explained/index.php/Passenger_transport_statistics. Accessed March 10, 2018.
8. Source: interview conducted at the Dutch National Institute for Public Health and the Environment – RIVM, recorded and transcribed under consent. The information available in English on this communication is limited. Thorough researches on how this information was produced and communicated are missing.
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