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Social hotspots life cycle assessment: A case study on social risks of an antimicrobial keyboard cover

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ABSTRACT

This article explores the application of social life cycle assessment (S-LCA) to products or technologies in their earliest developing phase. Indeed, it would be beneficial to have an overview of the social risks generated by novel products and understand what their potential supply chain would be like. To this end, this study presents a S-LCA study for identifying hotspots linked to a novel product: an antimicrobial keyboard cover integrating gold nanoparticles. Firstly, countries which could supply Europe with the input materials required in the system were identified, then by following the S-LCA methodology working hours and working functional hours were estimated. Ultimately, social risks were calculated by combining working functional hours with social risk levels and weights, concerning the relative importance of each category and sub-category.

The analysis helped to determine which countries could supply the materials needed and hence become part of the potential supply chain of antimicrobial keyboard covers integrating gold nanoparticles. Furthermore, it led to the identification of main social hotspots linked to each material used. In general, results show that the stakeholders most at risk of adverse social impacts across different sectors and countries are workers. Indeed, they may be affected on both their rights and work conditions, health and safety. The process of gold mining highlights the difference in terms of social risks between more developed countries, such as Australia and Sweden, and developing countries, such as South Africa. The production of chemicals presents a homogeneity in terms of risk hours associated to the considered European countries.

1. Introduction

Nanotechnology has proven to be fundamental to help addressing societal challenges in key areas such as health care, energy supply, transport, food industry and the environmental sector (Ali et al., 2020; Bolade et al., 2020; Borkowska et al., 2020; Nile et al., 2020).

Whilst researchers in the nanotechnology sector explore new paths for producing nanomaterials in an efficient way, and explore their potentials in tackling global challenges such as cancer treatment (Dreaden et al., 2011; Gonciar et al., 2019; Her et al., 2015; Ortega and Pankhurst, 2014), it is also our responsibility to avoid creating new problems while trying to solve others.

Under the 2030 Agenda of Sustainable Development, which has at its heart the 17 Sustainable Development Goals (17 SDGs) (United Nations, 2015), all UN member states have committed to the implementation of various policies aiming to end poverty and hunger in the world, provide enabling conditions for good health and well-being as well as along with political actions to promote sustainable industrialization, responsible production and consumption, and limit the effect of climate change, whilst preserving oceans and terrestrial ecosystems.

New technologies, such as nanomaterials, can have a fundamental role in achieving the 17 SDGs, on condition that the “leave no one behind” principle is applied (United Nations, 2015). Therefore, whilst going further in technological progress, tackling specific problems, and pushing economic development, it is also fundamental to improve social well-being.

When emerging technologies and products are examined from a social point of view, it is quite straightforward to recognise the social advantages and drawbacks related to their utilisation. However, this is only the tip of the iceberg; indeed, social aspects linked to the production chain should also be considered. Furthermore, as already stated in (Lehmann et al., 2013), “it is essential to include social aspects related to technology implementation in an early stage of technology development, as well as in a decision-making process for (already available)

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alternative technology options to avoid failing".

Social Life Cycle Assessment (S-LCA) is a methodology developed to assess:

- social and socio-economic risks, where risks represent "potential adverse impacts" and opportunities of improvements (Benoit-Norris et al., 2019);
- social performance of companies (where Social Organizational LCA is today preferable (Martínez-Blanco et al., 2015));
- positive and negative impacts related to the life cycle of products and services, as a results of the activity itself and/or the interactions of different stakeholders (Benoiˆt et al., 2009).

Social hotspots assessment is usually one of the results of S-LCA studies, and it mostly provides information about where controversies and problems concerning social themes are likely to be found (Benoiˆt et al., 2009; UNEP, 2020).

The main aim is to improve the socio-economic conditions of the stakeholders directly and indirectly involved in the product life cycle (Arcese et al., 2017). Therefore, the object of the evaluation is not the final product or service itself, but rather the network of companies comprising the supply chain. This includes the companies providing the intermediate materials required as inputs in the specific system under study as well as, those involved in the extraction of raw materials.

Amongst the other sustainability methodologies, S-LCA is the most recent one; indeed its development and improvement, followed by the construction of databases and tools for its application, started roughly ten years ago (Goedkoop et al., 2018b; Macombe et al., 2018; UNEP/SETAC, 2009). Therefore, it can be expected that the methods and tools employed may require further advancement and betterments (Zamagni et al., 2015).

Intrinsic to its nature and strictly dependent on the purposes of the study, S-LCA requires primary data from companies within the scope of the study, such as number of employees and demographic information, number of injuries/deaths *per* year, information on wages, policies in place to support well-being of employees, etc. (UNEP/SETAC, 2009). Therefore, results on how the company performs, and the identified hotspots are country-, temporal- and company-specific. Consequently, when novel technologies are assessed, the evaluation of the potential risks related to a possible supply chain can be challenging. However, having such a knowledge could be an opportunity to identify measures to minimise or avoid potential negative social impacts.

Generally, when emerging technologies are assessed according to life cycle assessment (LCA) methodology, ex-ante approach is employed. This approach helps in defining an inventory of data concerning a new technology based on forecasts related to future production scale, optimization of processes and creation of different scenarios (Arvidsson et al., 2018; Grimaldi et al., 2020; Thonemann et al., 2020). Furthermore, it may be employed for addressing issues related to the uncertainty of data related to processes in the early stages of development. Another issue is represented by the lack of information concerning the geographical context, of both background and foreground systems for future technologies. This is due to the non-existence of a supply chain, which in LCA it is often overcome by assuming the geographical location of both background and foreground systems. Whilst for the S-LCA knowing the geographical location of the system is a *sine-qua-non* condition for carrying out the study. Therefore, the practice of collecting information on the supply-chain by using input-output models have been adopted in S-LCA to identify the geography of the supply chain.

An example is the detailed Global Trade Analysis Project database (GTAP), which enables the identification of bilateral trades and, has been used by several authors to define the geographical context of the possible supply chains (van Haaster et al., 2017; Zamani et al., 2018). Another tool widely used is the Social Hotspots Database (SHDB) (Benoit-Norris et al., 2019), developed to provide information on the "social risks and opportunities by country and economic sector" related to labour rights, health and safety, governance, community (Benoit-Norris et al, 2012, 2019). SHDB has been built in compliance with the OECD Handbook on Constructing Composite Indicators recommendations (Mattes and Sloane, 2015). Data used are all publicly available information, from data sources such as intergovernmental databases, country statistics, NGO reports, trade union and academic papers. For instance, some of the sources are the International Labour Organization, UNICEF, the World Health Organization, Eurostat, the World Bank.

Up to now, researchers in the S-LCA field have been relying on tools such as the SHDB and input-output models to evaluate the risks or hotspots linked to established technologies in cases where no primary data was available. Some authors (Zamani et al., 2018) tried to couple input/output model data with the SHDB to identify the levels of risks and the main hotspots of the Swedish clothing consumption; whilst others (Souza et al., 2018) used the input/output model with sectorial data to assess the social effects of different scenarios of ethanol production in Brazil, considering the entire supply chain.

S-LCA has also been used to assist decision-making as in (Hosseinijou et al., 2014; Subramanian et al., 2018), where the methodology has been employed to make a comparison between concrete and steel as building material in Iran, and in the field of nano-enabled products, respectively. To the best of authors' knowledge, in scientific literature the number of papers on social life cycle concerning the nanotechnology sector is extremely low (Subramanian et al, 2016, 2018). Subramanian et al. (2018) focused on social impacts of a commercialised nano-enabled product trying to develop a quantitative social impact assessment (SIA), showing results as social benefits and costs. In (Subramanian et al., 2018) S-LCA was combined with multi-criteria value theory (MCVT), values from the MCVT were modified based on normalization and user weights, and then aggregated. By collecting primary data at company level for different social indicators, Subramanian et al. (2018) performed an assessment of the social performances of companies involve in the supply chain. Social indicator scores were estimated for the product understudy, and comparison with previously estimated social indicator thresholds was performed.

Differently from what it has been done in the past, in this paper we try to answer the questions: "how can we apply S-LCA methodology to products with a very low technology readiness level? How can S-LCA be applied when the supply chain is not defined yet?" We analyse what a potential supply chain for a novel product would be, and we focus on identifying the potential social risks, not performances, related to it. Specifically, we show how risks levels linked to each potential country-supplier might be quantified, by coupling input/output data with the risk levels collected from the SHDB (web application), applying weights estimated using information collected from a survey and using the multi-criteria decision analysis (MCDA) approach. The case study reported in this article refers to an antimicrobial keyboard cover integrating gold nanoparticles (Huang et al., 2020; Hwang et al., 2020), to be placed over the keyboards of computers and equipment located in hospital wards. This product has been selected as object of this study for two main reasons, it integrates nanoparticles, an emerging technology with global labour and markets estimated to double every 3 years, reaching up to $30 trillion market in 2030 (Tsuzuki, 2016). The other reason is because of the interests in hospitals in finding new solutions to overcome the issues of cross-infections amongst patients. Scientific studies showed that when caregivers are not compliant with hand-hygiene standards, cross-transmissions of pathogens amongst patients occur (FitzGerald et al., 2013; Haque et al., 2018; Otter et al., 2013). FitzGerald et al. (2013) highlighted the necessity of an educated hospital personnel on the causes and risks of bacterial spread and the necessity of implement interventions to lower the risks of cross-infections from surfaces. Some hospitals employ specific keyboard covers such as the Medigenic keyboard covers (Medigenic, 2019; Wilson et al., 2008) with an integrated "Clean-Me" alert system to communicate to the user when the keyboard needs to be cleaned with alcohol wipes (70%). The employment of antimicrobial keyboard covers, characterized by a continuous disinfection activity, aims to reduce the probability of cross-infections amongst patients without relying only on the hospital personnel to disinfect the surfaces (Rutala et al., 2006; Wilson et al., 2008).

The production of antimicrobial keyboard covers is comprised of two main activities: synthesis of nanoparticles and swell-encapsulation-shrink process, during which gold nanoparticles are embedded into the silicone matrix of the keyboard cover. The final product is a silicone keyboard cover that has absorbed gold nanoparticles and crystal violet (Huang et al., 2020). As reported in the scientific literature (Huang et al., 2020; Hwang et al., 2020) gold nanoclusters enhances the bactericidal activity of the crystal violet. Specifically, cysteine-capped gold nanoclusters [$Au_{25}(Cys)_{18}$] are synthetised by a chemical reduction process in milli-reactors (Huang et al., 2020).

In the swell-encapsulation-shrink process a photo-bactericidal solution composed of acetone, deionised water, aqueous solution with gold nanoparticles and crystal violet is prepared. Then, the keyboard cover is immersed in the solution and left to soak in it for 24 h (Hwang et al., 2020).

As previously reported in this section, antimicrobial keyboard cover is a product presenting a low technology readiness level with a market in the healthcare sector. The main purpose of the study is the identification of a potential supply chain for the antimicrobial keyboard cover, and the identification of the related potential social risks. Therefore, we use the S-LCA as a tool for decision-making, to consider and include the social aspects in defining the supply chain to produce gold nanoparticles embedded antimicrobial keyboard covers. The awareness of the potential social risks that can be associated with the procurement of raw and intermediate materials required in a production system, should be the basis for the development of a fair and (as much as possible) socially sustainable selection of suppliers.

2. Methods

The study has been carried out following the procedure reported in Fig. 1. The schematic shows the main actions identified for the application of the S-LCA methodology as reported in the "*Guidelines for Social Life Cycle Assessment of Products*" (Benoiˆt et al., 2009) and the SHDB manual (Benoit-Norris et al., 2019) for assessing the social risks of products or technologies. Following the characteristics of S-LCA described in (UNEP, 2020), the impact assessment approach employed in this study could be defined as a reference scale assessment (type 1). This approach should be employed when the purpose is to assess social performance or social risks. In this case study, the reference scales are not defined by who performs the study, but they have been defined and applied in the SHDB, for the determination of social risk levels.

In addition, identification of the main countries supplying the inputs (country-suppliers) and estimation of weights by means of a survey for the calculation of the risk assessment is carried out. Paragraphs 2.1, 2.2 and 2.3 present the procedure applied in determining the potential social risks associated to technologies and products and to assist decision making regarding the definition of potential supply chains.

2.1. Goal and scope

This paper presents an attributional approach for the application of the S-LCA methodology to identify a possible supply chain that minimises the social risks associated to the manufacturing of antimicrobial keyboard covers. The approach is an attempt to support the selection process of potential suppliers that may be involved in the supply chain of novel products. In addition, the assessment aims to identify the main hotspots and the type of stakeholders who may experience adverse social effects.

Considering the aims of the study, the approach described could easily remind of the ex-ante approach used in LCA and parallelisms could be drawn. Therefore, in order to not fall in any pitfalls, it must be pinpointed that the inventory concerning the material flows has been created by scaling-up/out the process developed at laboratory scale, assumptions on the process efficiency were applied, but no worst-case and best-case scenarios were defined. Then all the data on the import and export of different materials used for the definition of the supply-chain, the ones collected for the calculation of the working functional hours as well as the risk levels from the SHDB have been used as if the supply-chain was implemented nowadays. This happens even for ex-ante LCA; indeed, the most used databases are mainly static and use datasets referring to technologies that are employed nowadays, providing a short time validity for the future of a few years. Therefore, even though the foreground inventory is developed with an ex-ante approach the results could be partially represent a future situation. If an ex-ante social-LCA method for the identification of social hotspots were possible, it would require predictive elements during the various

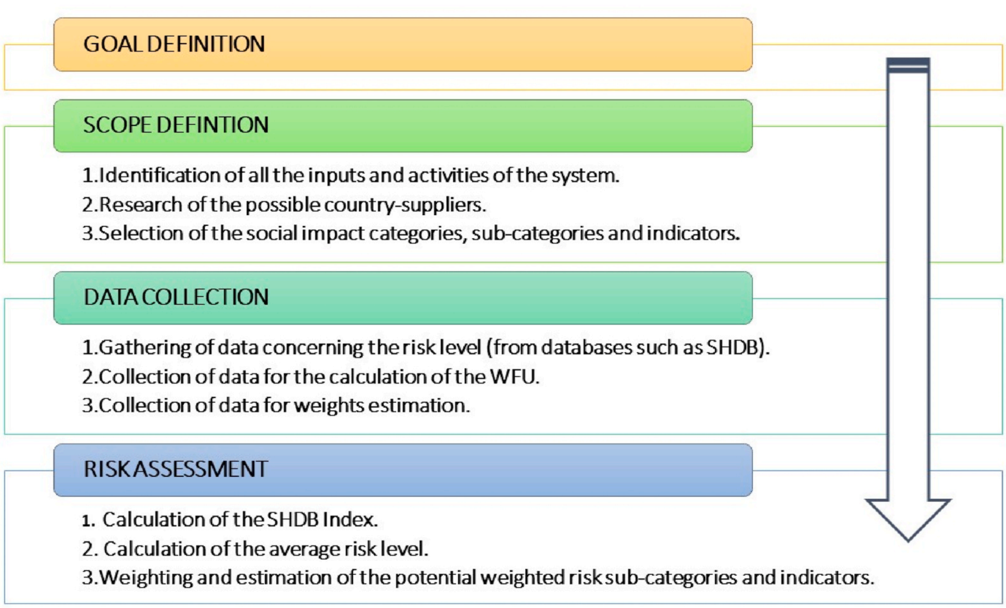

Fig. 1. Schematic of main steps of the approach proposed in this study for estimating social risks of new products and technologies.

steps of the compilation of the inventory concerning level of readiness of the technology, thus number of workers and working hours. Furthermore, assumptions on future global market relationships between countries and strong assumptions on future social conditions would be required.

2.1.1. Functional unit and system boundaries

The functional unit (FU) chosen for this study is the killing of pathogens and microorganisms that are transferred on the surface of the antimicrobial keyboard cover during the medical activities in European hospitals over a period of one year. The reference flow estimated to fulfil the functional unit is equal to 1.68 million of antimicrobial keyboard covers. It is also estimated that the European demand of gold for synthesising gold nanoparticles to be used in this specific application would be around 141 kg, equivalent to 0.005%–0.006% of average annual extraction of gold at global level. Indeed, the worldwide extraction of gold fluctuates between 2500 and 3000 tons each year (Grimaldi et al., 2020).

The reference flow was estimated based on the number of doctors and nurses across Europe in 2018 (European Commission, 2017; Eurostat, 2019a) and the assumption that the ratio between the number of doctors/nurses and electronic devices is 2:1.

Within the scope of the study, we aim to consider the following phases: manufacturing of silicone keyboard covers, synthesis of gold nanoparticles, incorporation of gold nanoparticles in the silicone matrix, and production of the main chemicals involved in the main production phases, as shown in Fig. 2, the foreground system. Precisely, all processes for which the antimicrobial keyboard cover manufacturer would have decisional power over the companies providing the input. Background processes, defined as those processes on which the manufacturer would not have a direct decisional power, such as generation of electricity used for the synthesis of one of the material inputs, have not been considered. While there is plenty of data on gold mining (Mancini et al., 2018b), it was very difficult to retrieve data on production of tetra-chloroauric acid. Therefore, it was decided to consider only the gold mining process and the synthesis of hydrochloric acid, which is one of the main chemicals used in the synthesis of tetra-chloroauric acid (King et al., 2015) and for which enough information was available.

The manufacturing of all capital goods was excluded from the scope of the study, as well as the production of electricity required for the synthesis of gold nanoparticles, use phase and end-of-life of the product.

Other processes excluded from the scope were the production of crystal violet. The exclusion was due to the impossibility of retrieving any information concerning the market of the product, traders and producers. The synthesis of the specific gold nanoparticles required in the system is described by (Huang et al., 2020), it is a novel synthesis method not yet adopted by companies synthetizing and selling gold nanoparticles. Therefore, because of a series of lack of essential information due to the low level of readiness of the technology, it was decided to cut-off this process from the system boundary. Production of silicones polymers was used as a substitute for the manufacturing of silicone covers. The preparation process of the antimicrobial keyboard covers was excluded due to the very low level of readiness of the process, which is still at laboratory scale and needs to be engineered and scaled out/up. This led to the decision to consider this process as part of the cut-off.

Proper waste management of products embedding metal nanoparticles is crucial for reducing the loss of valuable materials and possible environmental contamination. Up to the authors' knowledge, a process that would allow a recovery of metal nanoparticles from plastic and polymeric matrixes has not been developed yet, therefore a cut-off was applied. It must be noted that the market of nanoparticles is growing and likewise their utilisation. Hence, it could be foreseeable either to have nano-waste management sites where wastes are treated, or to have in place a circular ownership model, with companies selling the antimicrobial keyboard covers and taking them back at the end of their lifetime.

Stakeholders considered in this study are mainly workers, local community and society. Hence, the social topics selected for this study all refer to these groups of stakeholders.

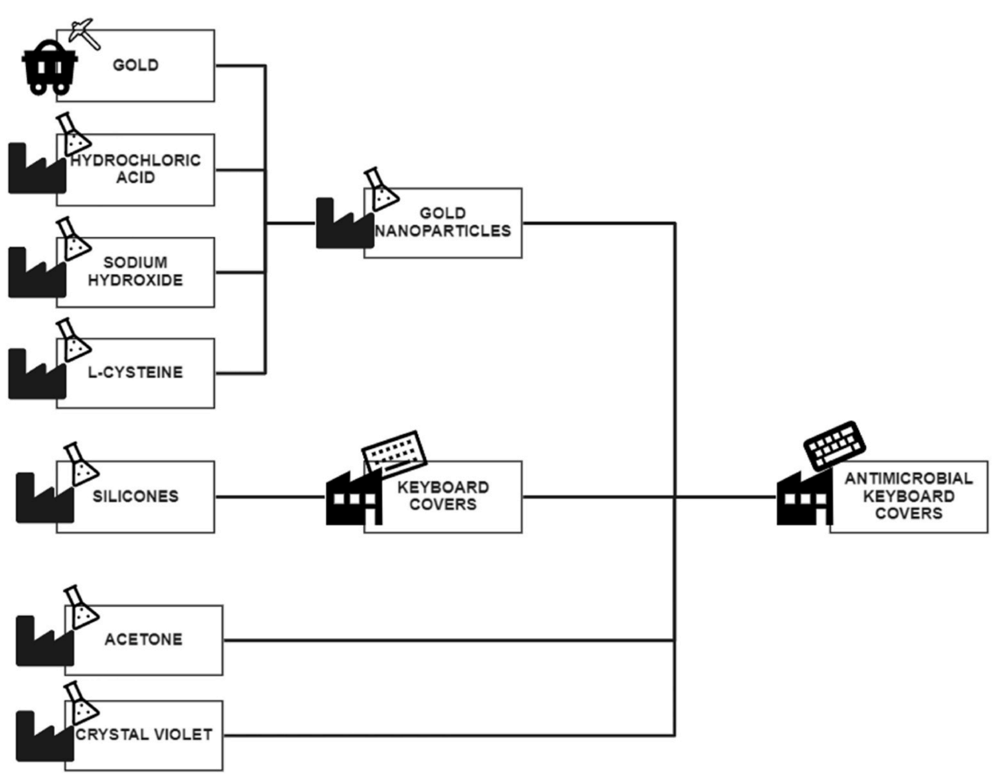

Fig. 2. Simple schematic of the entire system, reporting the main processes of the system.

The social topics relevant to the system understudy were selected based on the social impact categories or issues that have become relevant over the years or are taken into account by different guidelines and technical reports on the assessment of social impacts of chemical products and raw materials (European Union, 2017; Goedkoop et al., 2018a; Mancini et al., 2018a, 2018b; WBCSD World Business Council for Sustainable Development, 2016).

Precisely, the impact categories considered are labour rights and decent work conditions, health and safety, human rights, governance and community. For each, the SHDB provides an extensive list of subcategories. For example: labour rights and decent work conditions category comprises sub-categories such as child labour, forced labour, poverty, wage assessment. Each sub-category is associated to one or more indicators expressing the risk level based on different source of data either at country or sectoral level. In the case of freedom of association, there are several indicators expressing this social issue, such as risk that the country lacks or does not enforce collective bargaining rights and the right to strike. The full list of social impact categories, subcategories and indicators as presented in the SHDB and considered in this study is reported in Table SI1 (in appendix 4).

It has to be noted that data from the new version of the SHDB (Benoit-Norris et al., 2019) was used for two new sub-categories not included in the old version: "social benefits" and "discrimination and equal opportunities" and including their respective indicators.

2.2. Data collection and inventory

Data collection phase focused on the definition of a likely supply chain and gathering of all those data necessary to estimate the social risks for each country. A steady state of the trade patterns and social conditions worldwide was assumed, due to the impossibility of producing forecast models of future political, economic and social conditions of each country. It is a reasonable assumption, indeed often the social issues strongly depend on cultural and political issues which usually do not change in a short period of time.

The approach employed in this study is merely attributional; marginal suppliers were not investigated as it is usually done when a consequential approach is used (Ekvall et al., 2016; Pizzol and Scotti, 2017; Sacchi, 2018; Thomassen et al., 2008).

Firstly, this study investigated which countries would be either possible first tier suppliers or producers of the inputs required in our system. This was done by means of the "Observatory of Economic Complexity" (OEC) (Simoes et al., 2011), an open access visualisation tool using the BACI International Trade Database (Gaulier and Zignago, 2010). Contrary to the GTAP database, used in the SHDB, the OEC provides trade data of more specific class of products, classified by using the very detailed Harmonized Commodity Description and Coding System (HS) – Appendix 2, Supplementary Information. The utilisation of the tool allowed the identification of countries producing and exporting to Europe the chemicals necessary for manufacturing the antimicrobial keyboard covers. Then, we verified the existence of big market player industries in the selected countries, and we gathered data from the respective companies' websites, financial reports and sustainability reports, as reported in Appendix 3 in the Supplementary Information. The data collected refer to the number of employees, annual production, salaries, weekly labour hours, and these were used to calculate the number of working hours required for producing each chemical, as shown in Eq. (1) (Cassia et al., 2011; Petti et al., 2018; Ramirez et al., 2016).

$$Wh = W \times h \times n/p \tag{1}$$

where:

- Wh is the number of working hours to produce one kg of the desired product;
- W is the number of workers involved in the process;
- h represents the worked hours *per* week;
- n represents the number of working weeks *per* year;
- p is the amount of the annual total production *per* year, in kg.

Subsequently, the working functional hours (WFU), i.e. the necessary working hours to satisfy the functional unit, were calculated, as expressed in Eq. (2), where c represents the amount of each materials necessary to produce the functional unit:

$$WFU = Wh \times c \tag{2}$$

Generally, the data used in this paper refer to the year 2018; when no data for that year was available, we used data from 2017.

When data was not available in sustainability reports or other documentation available on the companies' websites, more generic data, such as statistics from the OECD website (OECD, 2019) and Eurostat (2019b) was used.

When required, the number of employees working on a specific plant or site was determined based on the plant production or capacity. As reported in Table 1, depending on the country, the WFUs may vary largely for the same material. This can be the result of the utilisation of proxy data, due to the lack of the primary data, a lower plant capacity and the different technological development among countries, that can be reflected in a higher number of employees *per* unit.

Once the selection of countries as possible suppliers for each one of the inputs was completed, the Social Hotspots Database (SHDB) was used for collecting the risk levels related to each country and the specific industrial sector. Prior to this step, it was necessary to associate each good to the corresponding industrial sector used in the GTAP model, employed in the SHDB.

2.3. Social Life Cycle Risk Assessment calculation and weighting

The SHDB provides a qualitative representation of the social risks, as low, medium, high and very high risk. Therefore, when it comes to analysing comparative studies, in which several sub-categories and indicators are used, it is hard to make a decision. For this reason, the risk levels were expressed numerically, by using the scoring suggested in the SHDB (Benoit-Norris et al., 2019), assuming: 0.1 for low risk, 1 for medium risk, 5 for high risk and 10 for very high risk. Then each risk score was multiplied by the WFU to give the SHDB index, expressed in risk hours, according to Eq. (3).

This enabled to obtain a SHDB index for all the sub-category indicators linked to a specific social issue, for all the countries selected as possible suppliers. The analysis included 67 indicators, describing issues linked to 22 sub-categories. In total, the indexes estimated were 1340.

$$SHDB\ Index = Risk\ score \times WFU \tag{3}$$

The SHDB indexes at indicator level are useful to compare the possible suppliers and to identify hotspots. However, these are not practical when it comes to making decisions, this is because is not easy to prioritize one social indicator over another, as it depends on the specific situation. Thus, it was decided to adopt a weighting system to express the results at sub-category and category level, that would allow the comparison of sub-categories as well as categories against each other.

Specifically, weights are used to indicate the relative importance of sub-categories/categories. A higher weight, associated to one subcategory/category rather than another, means higher relative relevance.

At indicator level, when no weights were allocated, a corresponding numerical value equal to 1 was assigned. Then, in order to estimate the risk hours associated to each sub-category, the average of the SHDB indexes *per* sub-category was calculated, as shown in Eq. (4), where n represents the number of indicators within the sub-category:

$$A = Avg\ SHDB\ Indexes\ = \frac{\sum_{i=1}^{n} SHDB\ Index_i}{n} \tag{4}$$

Table 1
Possible countries supplying the materials and chemicals necessary in producing antimicrobial keyboard covers, and the estimated working functional hours required in each country to produce the materials and chemicals necessary.

Material & activity	Identified possible supplier	Working Functional Hours (WFU)	Material & activity	Identified possible supplier	Working Functional Hours (WFU)
Gold (Mining)	*Australia*	4.86E+04	***Acetone (Production)***	*Belgium*	3.12E+02
	South Africa	2.34E+05		*Germany*	1.07E+03
	Sweden	2.10E+04		*Spain*	5.24E+03
Hydrochloric acid (Production)	*Germany*	8.48E-02	***Silicones (Production)***	*Brazil*	3.08E+02
	Italy	9.56E-02		*China*	6.55E+02
Sodium Hydroxide (Production)	*Belgium*	1.02E-01		*France*	5.53E+02
	Germany	5.20E-01		*Germany*	2.90E+02
	Italy	3.72E-01		*Italy*	2.90E+02
Cysteine (Production)	*USA*	8.30E-01		*Spain*	2.62E+02
	Spain	1.41E+01		*USA*	3.24E+02

The approach used to evaluate the weights is based on the analytical hierarchy process (AHP), developed in the 1990 by Saaty (1990), and already used in S-LCA and in others studies based on LC-approaches (De Luca et al, 2015, 2018, 2015; Król-Badziak et al., 2021; Nikkhah et al., 2019; Pineda-Henson et al., 2002; Putra et al., 2020; Ren et al., 2015; Wang et al., 2016). By employing the AHP, the problem or decisional goal is hierarchically broken down in different levels, which in our case are the social impact sub-category and the social impact category. Then, a pairwise comparison approach between elements is performed, as it allows to focus the judgment on a "pair of elements and compare them on a single property without concern for other properties or other elements" (Saaty, 1990).

The collection of data for estimating the various weights was based on the results of a survey created *ad hoc* for this purpose, entitled "Social Life Cycle Risk Assessment 4 Nano", which was sent to the Social LCA community to be completed between November 08, 2019 and January 08, 2020. In total, 46 S-LCA practitioners opened the link, 25 of them partially responded to the survey, whilst 16 of them completed it entirely. Participants were asked to make pairwise comparisons based on the relative importance of the sub-categories within the same impact category, and the impact categories themselves, on a scale from 1 to 10 in order of importance. The scores to each pair comparison were used to calculate an average attribute value within the same sub-category before calculating the weights (W), as in Eq. (5), where B represents the average attribute value within the same sub-category. In the case of categories, weights were calculated by using the same approach.

$$W = B \Big/ \sum_{i=1}^{n} B_i \tag{5}$$

Table 2 reports the weights evaluated by using this approach, meanwhile a more thorough explanation of the method is reported in appendix 2 in the SI.

Weights at category level ranged between 0.16 and 0.23, whilst at sub-category level the differences of results highly depended on the number of sub-categories to be compared within the same category. For the 11 sub-categories within the "labour rights and decent work conditions" category, the difference between the lower and the higher weights is 0.04 points, and more than 6 sub-categories got the same weight. These results could be an indication of the difficulties encounter by the participants of the survey in comparing the sub-categories proposed, indeed the higher standard deviation concerning the answer given to each question is equal to 2.58 (see Appendix IV, SI). Nonetheless, weights estimated by using information from the survey helped to incorporate and consider in the results the perspective of the society, in this case a small sample of it, and which social issues would be more accepted compared to others.

Then the final results, expressed in weighted medium risk hours *per* impact category *referring to the* FU, were estimated as reported in Eq. (6), where:

Table 2
Estimated weights for both social impact categories and sub-categories, estimated from a survey sent to the Social LCA community, for a total of 25 entries, and estimated by using a Multi Criteria Decision Analysis approach.

Social Impact Category	Criteria Weights	Social Impact Sub-category	Attributes weights
Labour rights and decent work conditions	0.23	Child Labour	0.12
		Forced Labour	0.11
		Poverty	0.10
		Wage assessment	0.09
		Working time	0.09
		Freedom of association, collective bargaining, and right to strike	0.08
		Unemployment	0.08
		Labour laws	0.08
		Social Benefits	0.08
		Discrimination	0.08
		Migrant workers	0.08
Health & Safety	0.23	Occupational Injuries & Death	0.66
		Occupational Toxics & Hazard	0.34
Human Rights	0.21	Indigenous Right	0.35
		Gender Equity	0.32
		High Conflict zones	0.33
Governance	0.18	Governance	0.6
		Legal system	0.4
Community	0.16	Access to hospital beds	0.27
		Access to drinking water	0.28
		Access to improved sanitation	0.25
		Children out of school	0.20

- A represents the average risk level at sub-category level, as in Eq. (4);
- WSC is the weight of each impact sub-category within the same impact category, and
- WC is the criteria weight estimated through the survey results, as in Eq. (5), and representing the weight at impact category level.

$$Potential\ Risk\ cat. = WC \times \sum_{i=1}^{n} A_i \times WSC_i \tag{6}$$

Once results for each impact category for the selected country and industrial sector have been estimated, they can be summed to give the total weighted medium risk hours *per* country and industrial sector.

3. Results

Results are presented in Table 3, Table 4, and Table 5 for each country-supplier and process considered in the study: synthesis of gold nanopartilces, manufacturing of clean silicone keyboards, chemicals required in the swell-encapsulation-shrink process, respectively.

In order to visualise the results, an intuitive colour scale, ranging from green (lower risk) to dark red (higher risk) was applied to the results of each impact category.

Table 3
Social risks estimated for each country providing materials for the synthesis of gold nanoparticles. Results are expressed in weighted medium potential risk hours *per* FU. The risk of each impact category has been estimated following Eq. (6), the sum of the risk at category level is reported in "Total" column.

Processes	*Country-Supplier*	*Labour rights & decent work conditions*	*Health & Safety*	*Human Rights*	*Governance*	*Community*	*TOTAL*
Gold (Mining)	Australia	1.75E+04	2.60E+04	1.19E+04	1.88E+03	4.13E+03	**6.15E+04**
	South Africa	1.81E+05	2.16E+05	1.31E+05	9.06E+04	7.83E+04	**6.97E+05**
	Sweden	1.10E+03	1.42E+04	1.19E+03	3.70E+02	4.78E+03	**2.16E+04**
Hydrochloric acid (Production)	Germany	2.52E-02	2.10E-02	3.43E-03	1.49E-03	1.38E-03	**5.26E-02**
	Italy	2.09E-02	9.99E-02	1.41E-02	3.05E-02	5.72E-03	**1.71E-01**
Sodium Hydroxide (Production)	Belgium	2.23E-02	1.06E-01	1.30E-02	3.95E-03	1.65E-03	**1.47E-01**
	Germany	1.54E-01	1.29E-01	2.10E-02	9.16E-03	8.44E-03	**3.22E-01**
	Italy	8.27E-02	3.89E-01	5.49E-02	1.19E-01	2.05E-02	**6.65E-01**
L-Cysteine (Production)	USA	2.46E+00	2.04E-01	1.72E-01	3.22E-02	7.77E-01	**2.94E+00**
	Spain	5.23E+00	1.47E+01	1.80E+00	1.22E+00	7.05E-02	**2.38E+01**

Table 4
Social risks estimated for each country providing silicones to produce keyboard covers. Results are expressed in weighted medium potential risk hours *per* FU. The risk of each impact category has been estimated following Eq. (6), the sum of the risk at category level is reported in the "Total" column.

Processes	*Country-Supplier*	*Labour rights & decent work conditions*	*Health & Safety*	*Human Rights*	*Governance*	*Community*	*TOTAL*
Silicones (Production)	Brazil	1.00E+02	5.15E+02	1.02E+02	5.40E+01	1.40E+02	**9.12E+02**
	China	9.99E+02	5.84E+02	4.89E+02	3.46E+02	3.05E+02	**2.72E+03**
	France	5.41E+01	5.78E+02	4.98E+01	4.78E+01	8.98E+00	**7.39E+02**
	Germany	7.17E+01	7.21E+01	1.17E+01	5.12E+00	4.72E+00	**1.65E+02**
	Italy	5.68E+01	3.04E+02	4.29E+01	9.27E+01	1.60E+01	**5.12E+02**
	Spain	6.37E+01	7.21E+01	1.17E+01	5.12E+00	4.72E+00	**1.57E+02**
	USA	1.77E+02	7.96E+01	6.71E+01	1.26E+01	2.75E+01	**3.63E+02**

Table 5
Social risk hours to produce acetone in different countries. Results are expressed in weighted medium potential risk hours *per* FU. The risk of each impact category is estimated following Eq. (6) and the sum of the risk at category level is reported in the "Total" column.

Processes	*Country-Supplier*	*Labour rights & decent work conditions*	*Health & Safety*	*Human Rights*	*Governance*	*Community*	*TOTAL*
Acetone (Production)	Belgium	2.96E+02	3.26E+02	3.68E+01	1.14E+01	5.06E+00	**6.75E+02**
	Germany	1.39E+03	2.65E+02	4.32E+01	1.88E+01	1.73E+01	**1.73E+03**
	Spain	1.08E+03	5.40E+03	3.74E+02	2.52E+02	1.61E+02	**7.27E+03**

It is important to note that the comparison between the different countries providing different goods was based on the specific quantity of material inputs necessary for the synthesis of gold nanoparticles, manufacturing of keyboard covers, and the preparation of the antimicrobial keyboard covers.

The method applied weights to enable the comparison of the impact categories against each other, and to aggregate all results for each country into a final score (reported in Table 3, Table 4, Table 5 as "total"). Hence, allowing for the identification of the country with the lowest social risks associated to the production of a specific product.

Table 6 reports the country-suppliers that present the best performance in terms of social risks, and shows the overall social risks associated to the procurement of materials from those countries to produce 1.68 million of antimicrobial keyboard covers.

As previously explained, Table 6 reports the selected best country-supplier for each of the input materials required for the manufacturing

Table 6
Total social risk hours and percentage contribution to the overall social risk hours due to the best performing potential country-suppliers of each material input taken into account in this analysis.

Material/process	Country-supplier	TOTAL Social Risk	% Contribution
Gold (Mining)	*Sweden*	2.16E+04	96.43
Hydrochloric acid (Production)	*Germany*	5.26E-02	0.00
Sodium Hydroxide (Production)	*Belgium*	1.47E-01	0.00
L-Cysteine (Production)	*USA*	2.94E+00	0.01
Silicones (Production)	*Spain*	1.57E+02	0.70
Acetone (Production)	*Belgium*	6.75E+02	3.01
	OVERALL	**2.24E+04**	**100%**

of antimicrobial keyboard covers integrating gold nanoparticles.

Apparently, gold mining is the activity with the highest social risks (in terms of social risks hours) with a contribution over 96%, followed by the production of acetone (3.01%) and silicones production (0.70%).

4. Discussion

4.1. Gold nanoparticles

- Gold Mining

The synthesis of gold nanoparticles requires several chemicals, such as a tetra-chloroauric acid, as gold precursor, sodium hydroxide, cysteine used to functionalize the gold nanoparticles and water.

Results for each material and country considered for the synthesis of gold nanoparticles are reported in Table 3.

South-Africa and Australia were identified as main producers of gold in the world and exporters to Europe. In addition, Sweden was considered to be the main producer of primary gold in Europe (Christian, 2018).

The weighted results highlight the difference between South Africa and western countries in all the social impact categories. Generally, Sweden has got the lowest outcomes, whilst Australia's results are higher by one order of magnitude than Sweden in all categories except for health and safety and community categories. Sweden presents the lowest risks associated to the health and safety category, mainly due to a higher ratio of employees *per* annual production of gold, compared with South-Africa and Australia. South Africa resulted to be the region with the highest risk hours for the human rights category. This is mainly due to the high risk of conflict, as expressed in the Heidelberg Barometer indicators of number of conflicts, maximum intensity and overall change of all conflicts in a country compared to the previous year (Benoit-Norris et al., 2019). The same occurred for the governance category, for which the risk levels concerning corruption, power and stability of the legal system are higher than for the other countries.

- Hydrochloric acid production, sodium hydroxide and L-cysteine

Hydrochloric acid is one of the chemicals required to synthetize tetra-chloroauric acid, it is used as precursor of gold in the synthesis of gold nanoparticles.

From the OEC data, the main players for its production and commercialisation are located in Europe, specifically in Germany and Italy. Overall, Germany performs better than Italy, even though the breakdown of the results shows minimal differences.

In the case of amino-acid L-cysteine (pharmaceutical grade), it was very difficult to identify the main producers at global level. Amino-acids are largely used in the food industry, especially in Asia, where the production is entirely for internal market demand.

We considered Spain as one of the possible producers for amino-acid L-cysteine, and we specifically used data from WAKER, as producer of L-cysteine from non-animal source (vegetarian-grade). We compared Spain with a traditional production process based in USA, in which L-cysteine is derived from feathers, human hair, bristles and hoover (Hashim et al., 2014). The differences between the production in Spain and USA is in the range of 2 orders of magnitude for the governance category, while they present the same order of magnitude for labour rights and decent work condition issue. Regarding the latter impact category, Spain has lower qualitative risk levels (from the SHDB), but due to the higher ratio of employee *per* annual production, it results to have higher potential risk hours than the USA. This is the reason behind the relative high difference shown in other categories, such as human rights and community, where Spain presents lower qualitative risk level than USA.

Based on the results reported in Table 3 the best potential suppliers of chemicals required for the synthesis of gold nanoparticles are: Sweden/Australia (for gold), Germany (for hydrochloric acid), Belgium (for sodium hydroxide), USA (for L-cysteine). In the case of gold, Sweden presents the lowest social risks.

4.2. Keyboard covers

As previously explained in 2.1, it was not possible to get any information concerning the first-tier suppliers or producers of the silicone keyboard covers. To overcome this obstacle, it was decided to include the production of silicones polymers. As it can be seen from Table 4, China and Brazil are the countries with the highest risk hours. This is mainly due to the high qualitative risk levels assigned in the SHDB to both China and Brazil, especially for the health and safety impact category. Whilst China presents the highest risks in all the impact categories, it must be highlighted that Brazil is comparable with USA, France and Italy. After China, Italy presents the highest risk hours for governance, mainly due to corruption risk. On the other hand, Italy presents one of the lowest risks for labour rights and work conditions. France, instead, shows a relevant risk connected to health and safety.

Spain is the country presenting the best performance in all the categories selected. Therefore, it could be selected as one of the favourite countries supplying such product, followed by Germany. Moreover, for European production, sourcing materials in Europe would help in having better environmental impacts, especially those related to transport of goods.

4.3. Swell-encapsulation-shrink process

In order to integrate the gold nanoparticles into the silicone matrix, the keyboard covers are left in a solution with acetone and crystal violet (Huang et al., 2020) for 24 h.

Production of crystal violet was neglected because of the limited data available on its global production and market competitors. For this step, we only considered the production of acetone, because this is required in high amounts in the process, leading to high potential risk hours.

From the results shown in Table 5, Spain seems to be the country with the highest amount of risk hours; this is mainly due to the high ratio of workers *per* annual production of acetone. On the other hand, Belgium seems to be the country with the lowest social risks linked to the production of acetone, and therefore, it could be a good supplier.

4.4. Overall

Results show gold mining being the activity with the highest social risks (in terms of social risks hours) with a contribution over 96%, followed by the production of acetone (3.01%) and silicones production (0.70%).

Therefore, the main hotspot of the identified supply-chain (Table 6) is represented by the mining sector in Sweden. Specifically, workers would be the most affected stakeholder category, mainly due to risks linked to the health condition and occupational safety. As well as for the chemical industry, where workers carry the highest social risks linked to both "labour right and decent work condition" and "health and safety" categories.

This is in line with results from (Subramanian et al., 2018) on a nano-cooper oxide dye. Results form that study identified in the workers the stakeholder mostly affected by the "social costs" of the production, whilst the community would have benefitted the most.

The case study presented is an example of the how S-LCA can be applied to a technology with a very low technological readiness level, indeed, for both the specific processes of synthesis of gold nanoparticles and antimicrobial keyboard preparation have been developed at laboratory scale. For this reason, this study presents some weakness and limitations. Firstly, it was not possible to assess the working hours associated to the laboratory activities. Then, the lack of data concerning annual production of specific chemicals or working hours contributed to increase the uncertainty of the inventory and results. Therefore, depending on the scope of the assessment, authors would recommend using sector data, when specific information are not available.

Another source of uncertainty is given by the allocation approach employed to calculate the working hours. Indeed, when necessary, an allocation approach based on physics relationship has been applied. Finally, it must be reminded of the underlying uncertainties of both the SHDB and the OEC tools.

When S-LCA is applied to a product that is not on the market, it is important to determine its potential supply chain, and the location of the possible suppliers. Decision on the procurement of materials depends on different criteria, one should be social impacts and performance of the supplying companies. A first screening can be done by applying the approach we propose. Indeed, we tried to determine the supply-chain based on the social risks associated to the main producers and exporters to Europe of the material-inputs required. Results of the social risks associated to a country-supplier are used to compare it with other competitors and decide on how the supply-chain would look like and where hotspots are located.

It is worth noting, that for a better understanding of the social trade-offs potential social benefits should have been included in the study. This was not possible, and we considered only risks. Indeed, it would be difficult to determine potential social benefits level, in the way it has been done in the SHDB with the social risks. From a qualitative perspective, benefits from the usage of the antimicrobial keyboard cover integrating gold nanoparticles would include a lower number of infections in patients, a lower possibility of contracting bacterial infections for the healthcare personnel, and benefits in terms of less legal actions against hospitals. Even though potential benefits of using the product are not accountable from a social point of view, it also carries with itself all the potential risks coming from its manufacturing. As almost all the country selected as possible suppliers are in Europe, the same communities would experience risks and benefits. It is important also highlighting that a risk can be seen as an opportunity, indeed in a scaling up production scenario when the producer company is proactive in each of the risk a positive impact can result.

The approach we propose should be applied as a first attempt to learn about the potential suppliers and the social risks and hotspots. The final decision should be guided by the results of the analysis and communication with the potential suppliers, to understand their opportunity to improve social conditions, how they should act towards their stakeholders and their propension in make changes that would improve their social impact. From a more formal perspective, incorporating S-LCA at the very early stage of the business development could have benefits to identify at the very beginning the action and compensating measures to implement to address the risks. In this case, the company would start this process in a position of advantage as it would already have information on some social topics and main social issues. In some cases, stakeholders would already have acquired knowledge and practical experience in collecting data and information helpful for the development of a CSR strategy.

5. Conclusions

In this paper we applied social life cycle assessment to a new emerging production system which is not yet in place, and we defined necessary methodological steps. These methodological steps allowed us to use the S-LCA as a tool for decision-making, and ultimately to consider and include the social aspects in defining the supply chain to produce gold nanoparticles embedded antimicrobial keyboard covers.

The case study presents an analysis at European level, considering the annual production of 1.68 million of antimicrobial keyboard covers.

The starting point was to build an understanding of the possible countries which could supply each input material required in the system. Subsequently, we collected specific data necessary for the calculation of the working functional hours. Data was gathered from sustainability reports and other sources, such as from the websites of the big companies located in the countries identified as possible suppliers of the materials understudy.

Qualitative data on the risk levels for several social impact subcategories and categories were collected from the Social Hotspots Database. Then, a score was assigned to each risk level, and by using the WFU, the risk hours *per* social indicators were calculated. By aggregating and weighting the results, it was possible to get results at sub-category level and category level. Generally, from the analysis of producers and exporters, it was highlighted that apart from gold and L-cysteine, the main possible providers of chemicals are based in Europe, where the social risks level are usually lower than in other countries. Furthermore, thanks to the weighting, it was possible to compare the results at subcategory and category levels, allowing the identification of different trade-offs.

The analysis performed highlighted that the social risks linked to mining activities are the main contributors to the total overall social risk hours coming from the processes considered in this study. Even though the quantity of mined gold accounted for this study is quite low, around 141 kg, compared with the quantity of other inputs, the social risks due to the mining activity are significantly higher that from the chemical sector.

As in Table 6, more than 96% of the total potential social risks linked to the best potential suppliers, are due to the mining activity, whilst about 3% is connected to the production of acetone.

Social issues concerning labour rights and health and safety have been identified as the main social hotspots, therefore workers are the potential mostly affected stakeholders.

As pointed out in the paper, we encountered many difficulties in quantifying the number of working hours because of the lack of data. In addition, the combination of sectorial risk levels with the WFU could lead to an increase of uncertainties in the results. Indeed, one of the main limitations of both the approach and study is the impossibility to have a high accuracy in the results, due to the general nature of the data that could be retrieved, and the fact that many social risks are linked to the behaviour of a single company. However, the analysis enables the exploration and understanding of the possible social issues that may be linked to products which are not on the market yet. Thus, the results could be used as a first screening to understand the most affected stakeholders and the main social hotspots; this is an important aspect to consider when identifying and selecting suppliers. In order to have more accurate results, one would need to have free access to specific databases on the market such as, the average number of employees at sector level *per* unit of mass and dollar of output, and the average number of working hours *per* week *per* sector.

Based on the difficulties encountered during this study and its results, authors identified three possible areas of investigation that would help in improving the application of the S-LCA methodology. Firstly, an identification of potential social benefits to be integrated with the social risk levels in the SHDB; secondly, a detailed analysis on the weighting approaches, their applicability based on the aim of the study and the data to be weighted.

Finally, future research on the application of the life cycle thinking approach to assess the sustainability of emerging technologies should focus on the integration of the three methodologies: S-LCA, LCC and LCA. For instance, results from Social Life Cycle Risk Assessment study could be used as basis for LCA on emerging technologies when there is no information on the geographical location of each activity, and for further sensitivity analysis.

CRediT authorship contribution statement

Martina Pucciarelli: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Writing – review & editing. **Marzia Traverso:** Supervision, Conceptualization, Resources, Writing – review & editing. **Paola Lettieri:** Supervision, Project administration, Funding acquisition, Writing – review & editing.

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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Appendix A. Supplementary data

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