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Trends in sensitivity analysis practice in the last decade

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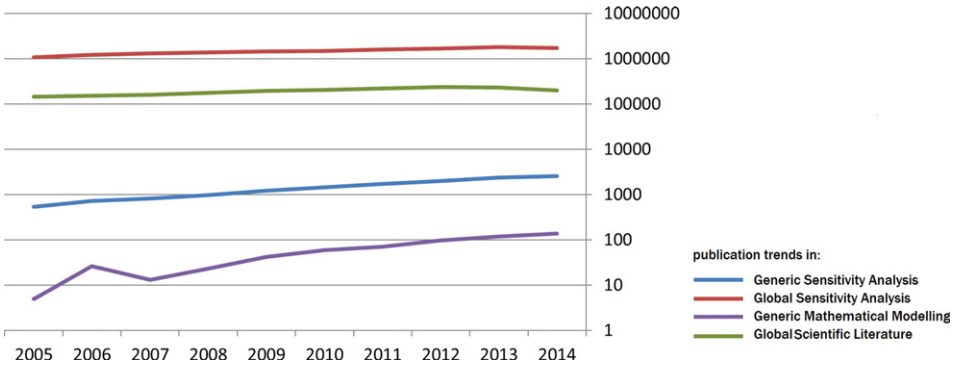
HIGHLIGHTS

- Sensitivity analysis is critical to gauge the relevance and plausibility of models.
- Sensitivity analysis is either overlooked or performed unsatisfactorily.
- We look at how things have changed over the last years performing bibliometric analyses.
- We see sign of improvements in the take up of global sensitivity analysis.
- Journals could play a role to improve responsible use of quantitative information.

GRAPHICAL ABSTRACT



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ABSTRACT

The majority of published sensitivity analyses (SAs) are either local or one factor-at-a-time (OAT) analyses, relying on unjustified assumptions of model linearity and additivity. Global approaches to sensitivity analyses (GSA) which would obviate these shortcomings, are applied by a minority of researchers.
By reviewing the academic literature on SA, we here present a bibliometric analysis of the trends of different SA practices in last decade. The review has been conducted both on some top ranking journals (Nature and Science) and through an extended analysis in the Elsevier's Scopus database of scientific publications.
After correcting for the global growth in publications, the amount of papers performing a generic SA has notably increased over the last decade. Even if OAT is still the most largely used technique in SA, there is a clear increase in the use of GSA with preference respectively for regression and variance-based techniques. Even after adjusting for the growth of publications in the sole modelling field, to which SA and GSA normally apply, the trend is confirmed. Data about regions of origin and discipline are also briefly discussed. The results above are confirmed when zooming on the sole articles published in chemical modelling, a field historically proficient in the use of SA methods.

1. Introduction

In "How to avoid a perfunctory sensitivity analysis", Saltelli and Annoni (2010) argued that the majority of published SAs were either local or one factor-at-a-time (OAT) analyses, relying on unjustified

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assumptions of model linearity and additivity. To the knowledge of the authors no dissent has been voiced in the literature against the paper's findings, which can be summarized as follow:

- Moving one factor at a time away from a fixed baseline in a multi-dimensional space of uncertain factors leaves the majority of that space unexplored. This is one of the consequences of the so-called curse of dimensionality, whereby the mass of a hyper-cube tends to concentrate in its edges and corners at increasing dimensionality – corners which are not visited if one moves factors away from their baseline one at a time.
- Further, moving one factor at a time leaves all interactions dormant as in order to activate them one needs to move more than one factor at a time, as known in statistical theory of the design of experiments. Experimental designs are in fact designed to efficiently uncover effects of various order e.g. main effects, second-order interactions, etc. Surprisingly many reported numerical experiments do not include a design at all.
- To obviate these shortcomings, global approaches to sensitivity analyses (GSA) are needed which are well described in the literature, but are applied by a minority of researchers.

2. Literature review

The literature review has initially been conducted by querying the databases of the high impact factor journals Science and Nature - whose impact factors in 2013 were 31.48 and 42.351 respectively (Thomson Reuters, http://thomsonreuters.com/journal-citation-reports, April 2015).

Search entries were set to exactly match the string "sensitivity analysis" anywhere in the text body for publications from 2005 to 2014. The retrieved documents have been thereafter individually scrutinized to assess their relevance for this research.

Approximately 30% of the raw database-return has been excluded because the content of the articles was found not related to the topic of sensitivity analysis of model output.

A pool of 66 publications was eventually used for the investigation (see Appendix for the searches' specification).

In most of the cases the articles could successfully be categorized into either OAT or GSA. In a few other cases an objective classification was not possible because the term "sensitivity analysis" was used generically in a context of uncertainty estimation.

For example, in Lentink et al. (2007) the sentence [*Sensitivity analysis: The performance maxima occur at the same wing configuration when we change body drag coefficient (2100%, 1200%), body weight (623%) and add the tail's contribution to lift (620% of wing lift)…*] clearly points to an OAT approach. In Carslaw et al. (2013) the sentence [*Here we carry out a variance-based sensitivity analysis of a global aerosol model to attribute the uncertainty in the aerosol first indirect forcing to uncertainties in the emissions and processes that control changes in aerosol over the industrial period…*] clearly refers to a GSA technique. Other less clear cut cases such as the one in Moreno et al. (2010), in which the model sensitivity seems to be conducted graphically, have been classified under the category "other".

2.1. Overall shares of SAs in top journals

The only inference permitted by Table 1 is that there still is dominance of OAT-type articles.

2.2. Overall shares of GSA in Elsevier's journals

An additional investigation in all Elsevier's journals using Scopus bibliometric search tools (www.scopus.com) enables a more extended review, although an article-by-article analysis is here clearly impractical. The queries adopted in this search are available in the appendix.

We performed various searches from 2005 onward to respectively assess:

1. The total number of articles (reviews, conference papers and letters have been excluded for comparability reasons). [TOT_PUB].
2. The total number of articles matching the string "sensitivity analysis" anywhere in the text body. The query also includes control strings to filter out entries not relevant to mathematical modelling. [TOT_SA].
3. The total amount of articles in 2 matching also GSAs methods (metamodel, high dimensional model representation, variance based, moment independent, elementary effect, regression). [TOT_GSA]=TOT_SA AND (technique_1 OR technique_2 OR … technique_N).
4. The total amount of articles in 1 also matching "modelling" or equivalent among the key words. [TOT_MOD].

Results are plotted in Fig. 1 on a logarithmic scale: GSA (violet line) seems to be gaining a slow but constant growing consensus.

2.3. GSA in the modellers' community

To assess their relevance, trends need to be adjusted by the global growth in publication they refer to. Fig. 2 presents the trends of TOT_SA and TOT_GSA over the global amount of documents published. Both trends clearly show the progressive community's interest in the area of SA (approximations fit linearly).

A similar trend in the number of SAs and GSAs is registered also relatively to the sole pool of publications on modelling (to which SA and GSA normally apply), after normalizing TOT_SA and TOT_GSA against the total number of publications in modelling TOT_MOD. Note how TOT_SA/TOT_MOD (blue line, left chart) is apparently undergoing a consistent expansion in the last couple of years.

Table 1
Articles in Science and Nature (own calculations).

Category	Description	Number of articles										Total
		2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	
One factor at a time (OAT)	SA performed by changing one input at a time while keeping the others at their baseline nominal values	6	5	5	5	3	3	3	–	2	6	39
Global SA (GSA)	SA performed by changing all the inputs simultaneously	2	–	1	–	–	1	1	1	4	–	10
Other	SA mentioned in contexts not related to uncertainty quantification or not involving model-based calculations.	2	1	1	1	2	2	2	2	1	3	17
	Total documents on SA	10	6	7	6	5	6	6	3	7	9	66
Total articles published	The total number of articles published in Science and Nature.	4109	4014	3768	3796	3587	3539	3581	3538	3397	3273	36,602

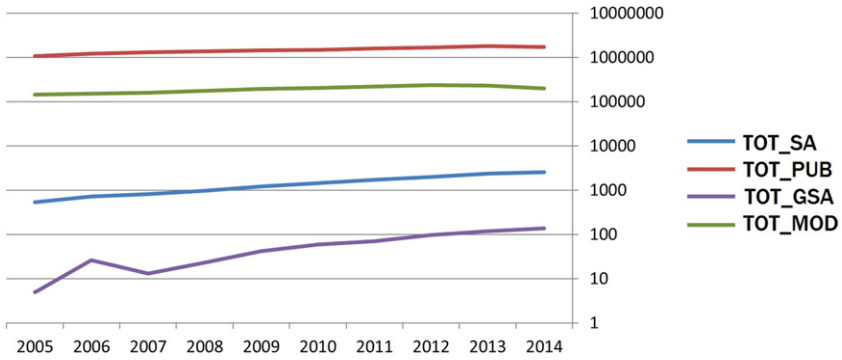

Fig. 1. Overall GSA trends (own calculations).

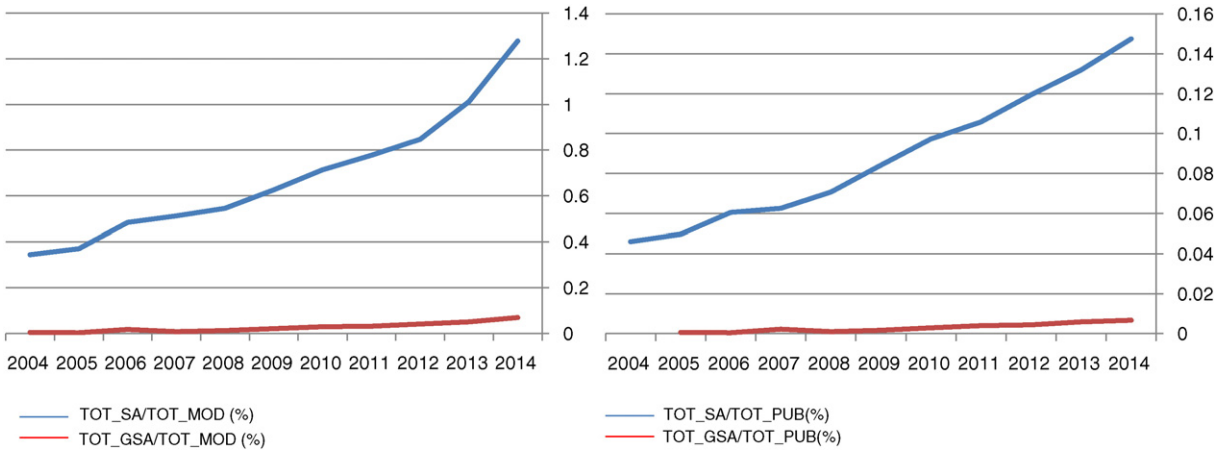

Fig. 2. Percentages of SA and GSA-reporting publications over the total.

2.4. 2.4. The impact of GSA in different scientific domains and country distribution

In the view of the above findings, we investigated the regional distribution of GSA, refining searches on the base of the country where the authors' affiliation is based. When more authors appear on the same article, all the countries of the authors' affiliations are accounted.

Fig. 3 displays the percentage distribution per country of approximately the 80% of TOT_GSA. Results are obtained employing the Scopus refine research tool directly on the query set for TOT_GSA. Fig. 3 shows, besides the usual suspects – US, Europe and UK, an important and supposedly growing contribution from China. Canada also plays a significant role.

Similarly, we refined the search for TOT_GSA to assess the volume and growth of GSA in the different scientific domains. According to the classification in Scopus, we grouped disciplines as follows as to account for approximately the 95% of TOT_GSA (see Scopus documentation on www.scopus.com/help.html):

- Chemistry: Chemistry, Pharmacology, Toxicology and Pharmaceutics, and Chemical Engineering
- Biology: Biochemistry, Genetics and Molecular Biology, and Agricultural and Biological Sciences
- Medicine: Medicine, Immunology and Microbiology, Neuroscience, and Veterinary
- Mathematics: Mathematics and Computer Science
- Physics: Physics, Astronomy, Material Science, and Energy
- Economics: Economics, Econometrics and Finance, and Decisional Science.

Fig. 4 shows that medicine and chemistry lead the rankings, possibly due to their massive use of models.

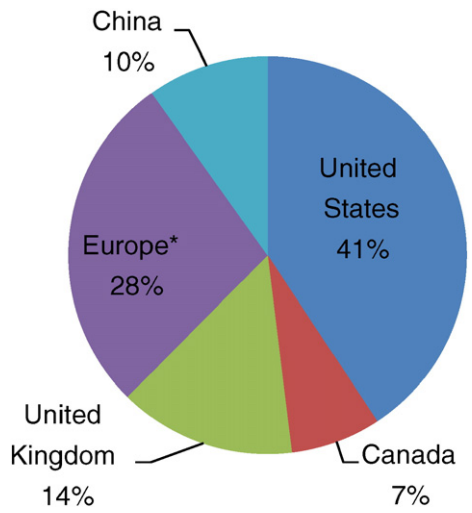

Fig. 3. Main players in a country distribution of GSA. *Europe includes 27 member countries without the UK.

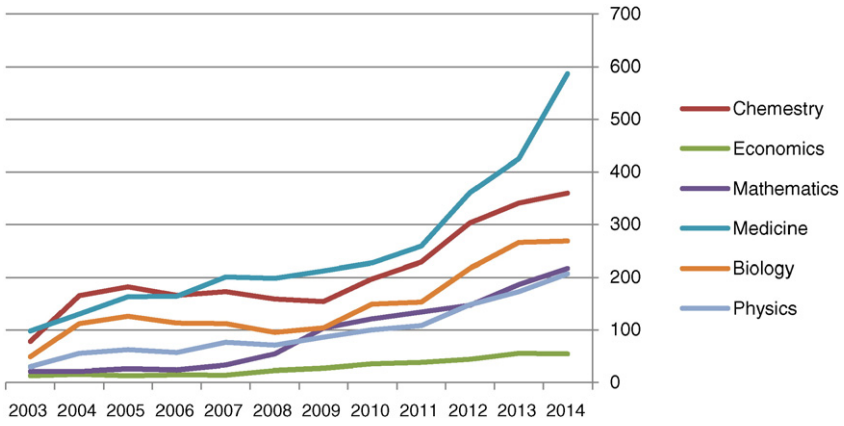

Fig. 4. GSA in the different scientific domains.

The case of mathematics is a special one – mathematicians have given a strong input to the discipline – just think of the works of the Russian mathematician Ilya M. Sobol, but are not in themselves heavy users of the methods or, when they are, their work is reported on disciplinary non-mathematical journals.

Interestingly, economics and decisional sciences – where sensitivity analysis should be crucial - remain at a lower level. In economic studies models often take the form of regression analyses, and in these settings it is customary to associate robustness with the value of the regression coefficients. At the same time, the discussion on the missing SA in econometrics is still ongoing (Leamer, 2010), with Kennedy (2007) listing sensitivity analysis as one of the commandment of applied econometrics:

> "*Thou shall confess in the presence of sensitivity. Corollary: Thou shall anticipate criticism.*"

Leeks (2014) identifies the lack of a sensitivity analysis in economics as a cause of significant problems, including the celebrated blunder of Rogoff and Reinhert:

> "*Similarly, two economists Reinhart and Rogoff, published a paper claiming that GDP growth was slowed by high governmental debt. Later it was discovered that there was an error in an Excel spreadsheet they used to perform the analysis. But more importantly, the choice of weights they used in their regression model was questioned as being unrealistic and leading to dramatically different conclusions than the authors espoused publicly. The primary failing was a lack of sensitivity analysis to data analytic assumptions that any well-trained applied statisticians would have performed*".

Fig. 4 also shows that though practitioners of sensitivity analysis have come a long way in the last twenty years to overcome disciplinary boundaries – also thanks to the SAMO series of conferences and summer schools[1] – the discipline remain still rather fragmented, with plenty of scope for fruitful cross-fertilization.

2.5. Chemical modelling: a leading sector in performing GSA?

We further refined our research to analyse trends in the sole field of chemical modelling, as a follow up of our publications for Chemical Review in 2005 and 2012 (Saltelli et al., 2005; Saltelli et al., 2012).

The two temporal series TOT_SA_chem and TOT_GSA_chem (queries' specifications available in the appendix) are again well approximated by linear trends. The total of articles in TOT_SA_chem alone over the 10-years period accounts for the 17% of the total volume of the generic TOT_SA. Similarly, TOT_GSA_chem accounts for the 8.5% of TOT_GSA, meaning that averagely one paper every two present mention to GSA.

By rescaling the publications' cumulative per cent growth rate between zero in 2004 and one hundred in 2014, we can appreciate the speed at which the number of papers in the various categories appears (Fig. 5). TOT_GSA_chem (green line) and TOT_SA_chem (violet line) exhibit the fastest growth, showing that GSA particularly has grown in chemical modelling more rapidly than in the generic literature.

2.6. Shares of GSA methods in the global literature

Fig. 6 shows the shares of the most used GSA methods in the global literature. Note that the difference among methods may not be clear cut as e.g. some forms of meta-modelling are based on HDMR.

The methods' shares remain approximately constant over time. Regression and variance based techniques are the most preferred and, on average, cover together up to the 65% of the total. Queries' specifications are available in the appendix.

3. Why modellers don't use statistical approaches for sensitivity analysis

In order for the take up of statistical methods for sensitivity analysis to be increased perhaps the reasons of modellers' resistance should be investigated. It is indeed a paradox that both natural and social scientists pay due attention to the design of an experiment when this involves specimens or individuals and become sloppy when the experiment is run 'in silico'.

As discussed in Saltelli and Annoni (2010), for natural scientist one issue is the existence of a 'baseline', a point in the space of the input factors where all input factors are set at their 'best' estimate, often referred to as 'nominal value'.

There is a certain resistance to depart from this baseline as a statistical sampling based approach would prescribe, because this baseline is perceived as a safe anchorage. Departing from it, the model may be perceived to move into "terra incognita", more practically, becoming unreliable or even crash away from the baseline.

Moving one factor at a time – as done in OAT – implies that whatever effect is observed on the output (including the case of no effect) can be

[1] The SAMO (sensitivity analysis of model output) conference series is devoted to advances in research on sensitivity analysis methods and their interdisciplinary applications. Main conferences are held every three years with the aim to bring together users of sensitivity analysis in all disciplines of science. Past editions have been held in Italy, Spain, USA, Hungary and France.
See <https://ec.europa.eu/jrc/en/event/training-course/samo-2016>.

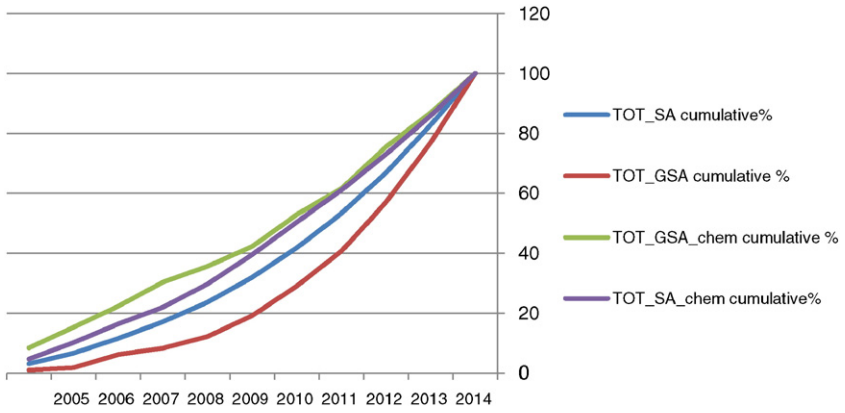

Fig. 5. GSA and SA cumulative percentages.

safely attributed to that factors, while statistical methods require some kind of formal analysis (such as e.g. in the simplest case a regression analysis).

Additionally, modellers rightly object that the use of statistical models for sensitivity analysis imply the capacity to draw a sample from the distribution of factors, when information about those distributions is often lacking. Yet, an OAT approach also presupposes a uniform volume in the hyperspace of the input factors, which is the de facto hypersphere whose surface is defined by the elementary steps.

Finally, there is a more worrying hypothesis about the scarce take up of global, explorative and statistics-based methods for sensitivity analysis well discussed by Econometrician Edward E. Leamer in an article entitled 'Tantalus on the Road to Asymptopia' on the Journal of Economic Perspectives. For Leamer, "One reason these methods [global sensitivity analysis] are rarely used is [that] their honesty seems destructive; or, to put it another way, a fanatical commitment to fanciful formal models is often needed to create the appearance of progress" (Leamer, 2010).

Very simply, being complacent about the style of one's sensitivity analysis may thus become a way to protect one's preferred inference from unwanted disturbances: in the age of p-hacking this is indeed a worrying hypothesis.

4. Conclusions

Our analysis points to two main results: first, the increasing share of articles that use sensitivity analysis, though this increase does not transmit to the high end journals Science and Nature. Second, a progressively increasing fractional share in the use of global sensitivity analysis techniques, with a positive trend supported independently from the set queries. These results suggest that, although traditional techniques of sensitivity analysis are by far still prevailing at the time of the present article, GSA could possibly displace those techniques in future. Toward that direction, top generalist journals could help by publishing review works on good practices of sensitivity analysis: Chemical Reviews did so in 2005 (with an update in 2012, Saltelli et al., 2012) probably contributing in pushing chemical modelling among the leading sectors employing GSA techniques for the calibration of their models.

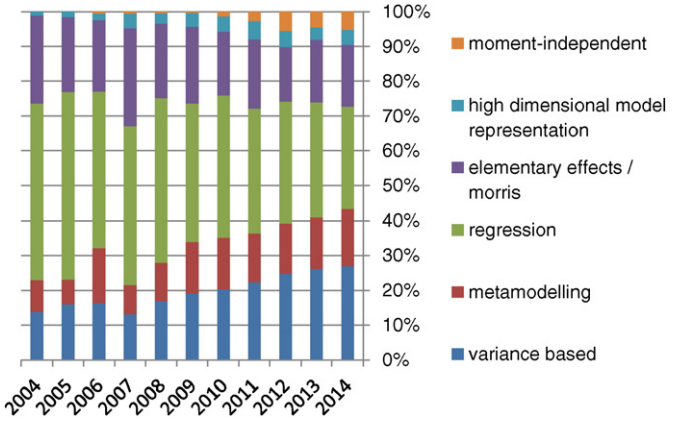

Fig. 6. Approximate shares of GSA methods.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.02.133.

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