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On the Numerical Accuracy of Spreadsheets

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Abstract

This paper discusses the numerical precision of five spreadsheets (**Calc**, **Excel**, **Gnumeric**, **NeoOffice** and **Oleo**) running on two hardware platforms (i386 and amd64) and on three operating systems (Windows Vista, Ubuntu Intrepid and Mac OS Leopard). The methodology consists of checking the number of correct significant digits returned by each spreadsheet when computing the sample mean, standard deviation, first-order autocorrelation, F statistic in ANOVA tests, linear and nonlinear regression and distribution functions. A discussion about the algorithms for pseudorandom number generation provided by these platforms is also conducted. We conclude that there is no safe choice among the spreadsheets here assessed: they all fail in nonlinear regression and they are not suited for Monte Carlo experiments.

Keywords: numerical accuracy, spreadsheet software, statistical computation, **OpenOffice.org Calc**, Microsoft **Excel**, **Gnumeric**, **NeoOffice**, GNU **Oleo**.

1. Numerical accuracy and spreadsheets

Spreadsheets are widely used as statistical software platforms, and the results they provide frequently support strategic information. Spreadsheets intuitive visual interfaces are preferred by many users and, despite their weak numeric behavior and programming support (Segaran and Hammerbacher 2009, p. 282), as said by B. D. Ripley in the 2002 Conference of the Royal Statistical Society opening lecture “Statistical Methods *Need* Software: A View of Statistical Computing”):

*Let's not kid ourselves: the most widely used piece of software for statistics is **Excel**.*

Additionally, the European Spreadsheet Risks Interest Group (<http://www.eusprig.org/>) relates that many corporations use spreadsheets to account big financial transactions. If the accuracy is poor, uncontrolled errors are likely to cost huge amounts of money. It is, therefore, of paramount importance to assess the accuracy of this kind of software artifacts in order to avoid disasters (Croll 2009; Powell *et al.* 2009).

Spreadsheets are widely employed by the scientific community in many applications, being a few recent examples the works by Aliane (2008), who uses **Excel** for building interfaces that ease the analysis of simulation charts for control systems, by Bäckman (2008), who shows how to use **Excel** in linear programming, by Bianchi *et al.* (2008), who use **Excel** for calculating the optimal treatment in a radiobiological evaluation, by Dzik *et al.* (2008), who propose a statistical process control using spreadsheets for training hospital employees, by Zoethout *et al.* (2008) who present a methodology for calculating alcohol effects or drug-alcohol interactions using spreadsheets and, among many others, by Roth (2008) who employs spreadsheets for the design of critical treatments, more specifically, dose control of high-voltage radiotherapy. With easy-to-use, intuitive interfaces and abstaining the user from mathematical formulas by function selection, they have won the preference of many users.

The scientific community seems to ignore, nevertheless, the vast literature that reports numerical problems that might preclude the use of spreadsheets in serious research (see, for instance, Apigian and Gambill 2004; Knüsel 1998, 2005; Kruck 2006; Lindstrom and Asvavijnijkulchai 1998; McCullough 2000, 2004; McCullough and Heiser 2008; McCullough and Wilson 1999, 2002, 2005; Nash 2006).

One should expect that after a critical assessment is made about a spreadsheet, future versions should be free of mistakes. But, as pointed by Heiser (2006); McCullough (2004); McCullough and Heiser (2008); Yalta (2008) this is often not the case.

In this article we used the methodology developed by McCullough (1998, 1999) and applied by Altman (2002); Bustos and Frery (2006); Keeling and Pavur (2007); McCullough (2000); Vinod (2000); Yalta (2007); Yalta and Yalta (2007) for the assessment of spreadsheets in a notebook with an i386 CPU (32 bits) and a desktop iMac with an amd64 CPU (64 bits). Regarding the operating systems, we used GNU/Linux Ubuntu Intrepid kernel 2.6.27-14-generic and Microsoft Windows Vista SP1 on the i386 CPU, and Mac OS X Leopard on the amd64 CPU.

We present the analysis of five spreadsheets running in up to three operational systems: Microsoft **Excel** 2007 for Windows and 2008 for Mac OS (Microsoft Corporation 2007), **Gnumeric** 1.8.3 for Ubuntu and 1.9.1 for Windows (The **Gnumeric** Team 2007), **NeoOffice** 2.2.5 Patch 7 and 3.0 Patch 1 for Mac OS (Planamesa, Inc. 2009), GNU **Oleo** 1.99.16 for Ubuntu (Free Software Foundation 2000) and **OpenOffice.org Calc** 2.4.1 for Ubuntu and Windows, and version 3.0.1 for all three operational systems (Sun Microsystems Inc. 2009). Table 1 shows a summary of the platforms and versions here assessed. These are the latest stable pre-compiled versions available for each platform at the time the experience was conducted, with the exception of the development release of **Gnumeric** for Windows, which was the only build available of that spreadsheet for such platform. This diversity is due to different hardwares, operating systems, versions and implementations may produce different numerical precision results. In fact, we observe such behavior in Section 4, and in Section 5 we conclude that

Platform		Calc		Excel		Gnumeric		NeoOffice		Oleo
Hardware	OS	2.4.1	3.0.1	2007	2008	1.8.3	1.9.1	2.2.5	3.0	1.99.16
i386	Windows	✓	✓	✓			✓			
	Ubuntu	✓	✓			✓				✓
amd64	Mac OS		✓		✓			✓	✓	

Table 1: Platforms and versions.

certain spreadsheets versions running in specific operating systems are advisable for particular operations.

The analysis is performed checking the number of correct significant digits returned by each spreadsheet when computing the sample mean, standard deviation, first-order autocorrelation, F statistic in one-way ANOVA tests, linear and nonlinear regression, and various distribution functions. The quality of the algorithms implemented for computing pseudorandom numbers is also discussed.

The rest of the paper unfolds as follows. Section 2 presents the historical background of these spreadsheets. Section 3 discusses the methodology for assessing the accuracy of the spreadsheets under consideration. Sections 4 and 5 present the results, discussions and lines for future research.

2. Historical background

Beginning with the suit **StarOffice**, the **OpenOffice.org Calc** spreadsheet was released in 1999. Its source code was released under the LGPL (Lesser General Public License, [Free Software Foundation 2007b](#)) in 2000, gathering a community of developers around its improvement and development of new functionalities. **Calc** currently offers almost all of the functions available in **Excel**, and many new other functions are included in each release. The add-ons mechanism included in the last version aims at allowing users to easily incorporate new functionalities without reinstalling the main core system.

Microsoft **Excel** for Mac OS was introduced to the market in 1985 as an alternative for **Lotus 1-2-3**, the most-used spreadsheet at the time. The first Windows version was issued in 1987. The greatest differential was the graphical interface which, allegedly, made its use easy by providing an intuitive access to its functionalities. Version 5.0 was introduced in 1993, supporting **Visual Basic for Applications** for the creation of macros to automate procedures ([Özkaya 1996](#)). Since 2007 it uses a new file type structure by default: the OOXML (Office Open XML), a Microsoft copyrighted format which is not fully compatible with other spreadsheets. The latest version, available only for Mac OS, is the 2008 and the 2007 for Windows. It also incorporates a mechanism for add-ons, but incompatible with **OpenOffice.org**.

Gnumeric 0.3 was released in 1998 by the GNU Project. It was intended to be a free (under GPL, General Public License, [Free Software Foundation 2007a](#)) alternative to commercial spreadsheets. Its original focus is on accuracy rather than on other facilities.

Since 2003 and now as the leading open source office suit for Mac OS, **NeoOffice** started as an X11-independent implementation. It was released using source code from the **OpenOffice.org**

suit, and it can be easily installed under the Acqua windows system. It claims that its current version provides all the features included in **OpenOffice.org Calc**, with improved speed and other functionalities (almost all related to interface and media support) common to Mac OS applications. Such improved speed may have impact on the numerical properties of the suite. It supports many of the add-ons provided by **OpenOffice.org**.

Oleo used to be the main GNU spreadsheet. It can be used both with a graphical interface or in character mode. The first operational interface for the X Windows System was released in 1994. Many of its functions are loaded from the GNU Scientific Library (**GSL**, Galassi *et al.* 2003), a powerful numerical engine, but none of the functions herein assessed belongs to **GSL**. **Oleo** project has no maintainer currently, and no references about its numerical properties were found in the literature.

3. Accuracy measurement

There are three kinds of errors that may appear in numerical computation: cancellation, accumulation, and truncation errors (Kennedy and Gentle 1980). These errors are due to the finite nature of binary computer representation of numbers (Knuth 1998, Chapter 4), and to negligent implementation of functions.

Since the particular type (or types) of errors into which an algorithm may incur depends on many factors (implementation, dataset, hardware and operational system, to name a few), extremely careful software development is always required.

In the following we will review the methodology employed for assessing accuracy of simple statistical functions, provided one does not have access to the algorithms they employ. In such situation, the evaluation must rely on the results those functions provide when used in special datasets.

Because of the lack of implementation details from some vendors (e.g., Microsoft) and the hard task required for analyzing source code, as previously said, we adopted the user evaluation viewpoint for assessing the reliability of spreadsheets. That is, we used each spreadsheet to calculate functions for different datasets, from which we know the *exact* (certified) answers. Comparing these answers with the values obtained from each spreadsheet we have a measure of accuracy: the *number of correct significant digits*.

3.1. Base-10 logarithm and correct significant digits

One of the most convenient measures for comparing two numbers consists in computing the absolute value of the relative error, and taking its base-10 logarithm:

$$LRE(x, c) = \begin{cases} -\log_{10} \frac{|x-c|}{|c|} & \text{if } c \neq 0, \\ -\log_{10} |x| & \text{otherwise,} \end{cases} \quad (1)$$

where x is the value computed by the software under assessment and c is the certified value. *LRE* (*Log-Relative Error*) relates to the number of significant digits that were correctly computed. For instance, considering $x_1 = 0.01521$ and $c_1 = 0.01522$, then $LRE(x_1, c_1) = 3.182415$. Moreover, if $x_2 = 0.0000001521$ and $c_2 = 0.0000001522$, then $LRE(x_2, c_2) = 3.182415$. In both cases we say that “the number of correct significant digits is approximately 3”.

In the following we adopt the convention of reporting one decimal place whenever $LRE(x, c) \geq 1$, zero if $0 \leq LRE(x, c) < 1$ and “–” otherwise; there is no worse situation than “–”.

3.2. Datasets and certified values

The *Statistical Reference Datasets* from the (American) [National Institute of Standards and Technology \(1999\)](#), NIST for short, were utilized as benchmarks. We used four kinds of datasets to assess the reliability of univariate summary statistics, analysis of variance, linear and nonlinear regression. They consist of nine, eleven, eleven, and twenty-seven datasets respectively, classified in three levels of difficulty: *low*, *average* and *high*.

For univariate summary statistics, analysis of variance, and linear regression, each dataset has certified values calculated using multiple precision arithmetic to obtain 500 digits answers that were rounded to fifteen significant digits. The same procedure was applied for nonlinear regression to achieve eleven significant digits.

NIST provides both observed (real world) and constructed data. For univariate summary statistics, low difficulty data are `Lew`, `Lottery`, `Mavro`, `Michelso`, `NumAcc1` and `PiDigits`; the first four being observed, and the last two constructed. `NumAcc2` and `NumAcc3` are average difficulty data and `NumAcc4` is the only high difficulty dataset for univariate summary statistics; they are all constructed.

NIST offers nine datasets for assessing the precision of ANOVA statistics, based on the proposal by [Simon and Lesage \(1989\)](#): `SmLs01`, `SmLs02` and `SmLs03` with low difficulty; `SmLs04`, `SmLs05` and `SmLs06` with average difficulty; and `SmLs07`, `SmLs08` and `SmLs09` with high difficulty. Two observed datasets are also provided: the low difficulty `SiRstv`, and the average difficulty `AtmWtAg`.

For linear regression, NIST gives `Norris` and `Pontius` observed datasets with low difficulty, `NoInt1` and `NoInt2` generated datasets with average difficulty, and `Filip`, `Longley`, `Wampler1`, `Wampler2`, `Wampler3`, `Wampler4` and `Wampler5` datasets with high difficulty, being the first two observed and the last five generated. The models associated to these datasets are: three linear, one quadratic, one multilinear, and six polynomial.

There is a diversity of nonlinear regression datasets supplied by NIST. Eight have low difficulty: `Misra1a`, `Chwirut2`, `Chwirut1`, `DanWood`, `Misra1b`, `Lanczos3`, `Gauss1` and `Gauss2`, being the first five observed and the remaining generated. Average difficulty data are `Kirby2`, `Hahn1`, `Nelson`, `Misra1c`, `Misra1d`, `Roszman1`, `ENSO`, `MGH17`, `Lanczos1`, `Lanczos2` and `Gauss3`, where the first seven are observed and the other generated. Finally, high difficulty data are `MGH09`, `MGH10`, `Thurber`, `BoxBOD`, `Rat42`, `Ecker1e4`, `Rat43` and `Bennett5`; the first two generated and the rest observed. There are four rational, sixteen exponential, and seven miscellaneous models for these data.

Regarding the distribution functions, those results obtained with `Mathematica 5.2` by [Yalta \(2008\)](#) were used. These values are certified to be accurate to six significant digits for all the distribution functions here assessed.

4. Results

Both the spreadsheet version and the hardware/software platform where it is used are factors that potentially may have some degree of influence. At the moment of this assessment,

Datasets	Calc	Excel	Gnumeric	NeoOffice	Oleo
Lew (l)	15.0	15.0	15.0	15.0	15.0
Lottery (l)	15.0	15.0	15.0	15.0	15.0
Mavro (l)	15.0	15.0	15.0	15.0	15.0
Michelso (l)	15.0	15.0	15.0	15.0	15.0
NumAcc1 (l)	15.0	15.0	15.0	15.0	6.6
PiDigits (l)	15.0	15.0	15.0	15.0	15.0
NumAcc2 (a)	14.0	14.0	15.0	14.0	13.9
NumAcc3 (a)	15.0	15.0	15.0	15.0	6.6
NumAcc4 (h)	13.9	13.9	15.0	13.9	7.6

Table 2: *LREs* for the sample mean.

the latest stable version of each spreadsheet for the latest stable version of each operating system was used, namely, **Excel** 2007, **Gnumeric** 1.9.1, and **Calc** 2.4.1/3.0.1 were run on Microsoft Windows Vista; **Gnumeric** 1.8.3, **Calc** 2.4.1/3.0.1 and **Oleo** 1.99.16 on GNU/Linux Ubuntu Intrepid; and Microsoft **Excel** 2008, **NeoOffice** 2.2.5/3.0 and **Calc** 3.0.1 on Mac OS X Leopard 10.5.6 (see Table 1).

The *LRE* values, see Equation 1, were computed using R 2.8.0 (R Development Core Team 2009) on GNU/Linux Ubuntu Intrepid (kernel 2.6.27-14-generic) whose excellent numerical accuracy has been assessed by Almiron *et al.* (2009).

Another important issue is the model representation in linear and nonlinear regressions. In previous works, the operator precedence interpretation led to wrong assessments (see Berger 2007), for instance **Excel** computes -1^2 as 1, while R computes the same operation as -1 . We used full parenthesis in all models to avoid such problem.

This section presents seventeen tables and a discussion, the later devoted to pseudorandom number generators (Section 4.5). The tables discuss results obtained when computing univariate statistics, namely, the sample mean (Table 2), the sample standard deviation (Table 3) and the sample first-lag autocorrelation (Table 4), analysis of variance (ANOVA, Table 5), linear (Table 6) and nonlinear (Tables 7, 8, 9 and 10) regressions and distribution functions (Tables 12, 13, 14, 15, 16, 17, 18 and 19). Each table presents *LREs*, whenever the procedure is natively available in each spreadsheet/version/platform. In those cases where the results of at least two versions coincide, they are presented only once.

4.1. Univariate summary statistics

All spreadsheets offer specific functions to calculate the sample mean and standard deviation. In **Calc**, **Excel**, **Gnumeric** and **NeoOffice**, the sample mean can be computed with the **AVERAGE** function, and the standard deviation with the **STDEV** function. **Oleo** offers the functions **AVG** and **STD**, respectively.

Table 2 shows the *LREs* when computing the sample mean; the expression $\bar{x} = n^{-1} \sum_{i=1}^n x_i$ was used to compute the certified values. Each column presents the results of all considered versions of each spreadsheet since they presented no differences.

We observe that **Gnumeric** presents the best results among all platforms, achieving the highest

Datasets	Calc	Excel 2007	Excel 2008	Gnumeric	NeoOffice	Oleo
Lew (l)	15.0	15.0	15.0	15.0	15.0	15.0
Lottery (l)	15.0	15.0	15.0	15.0	15.0	15.0
Mavro (l)	12.9	12.9	9.4	12.9	12.9	8.8
Michelso (l)	13.8	13.8	8.2	13.8	13.8	8.2
NumAcc1 (l)	15.0	15.0	15.0	15.0	15.0	–
PiDigits (l)	15.0	15.0	15.0	15.0	15.0	15.0
NumAcc2 (a)	15.0	11.5	11.5	15.0	15.0	12.5
NumAcc3 (a)	9.4	9.4	1.4	9.4	9.4	–
NumAcc4 (h)	8.2	8.2	0	8.2	8.2	–

Table 3: *LREs* for the sample standard deviation.

possible precision in every situation. **Calc**, **Excel** and **NeoOffice**, interestingly, attained the same precision with every but two datasets, **NumAcc2** and **NumAcc4**, which pose average and high difficulty, respectively. **Oleo** presented the worst results, with problems mainly in datasets with average and high difficulty.

Table 3 presents the results of assessing the precision when computing the standard deviation, whose certified values were computed with the expression

$$s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}}.$$

Calc, **Gnumeric** and **NeoOffice** exhibited similar behavior, achieving the same results for all datasets, with bad results for **NumAcc3** and **NumAcc4**. **Excel 2007** presented similar results to **Calc**, **Gnumeric** and **NeoOffice**, except for the dataset **NumAcc2**, for which it was worse. **Excel 2008** has several problems with four datasets, two of them of low difficulty. Again, the worst results were produced by **Oleo**.

Excel 2007 results for sample mean and standard deviation match with those calculated in [McCullough and Wilson \(2005\)](#) and confirmed by [McCullough and Heiser \(2008\)](#).

The first-order autocorrelation certified values were calculated using the expression

$$r_1 = \frac{\sum_{i=2}^n (x_i - \bar{x})(x_{i-1} - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2}.$$

No spreadsheet provides a specific function for computing this quantity, and it is not possible to calculate it as a simple correlation using the **CORREL** function. Consider the sample $a_1, a_2, \dots, a_{n-1}, a_n$; the first-lag autocorrelation can be computed dividing the sample covariance between a_1, \dots, a_{n-1} and a_2, \dots, a_n , divided by the sample variance of $a_1, a_2, \dots, a_{n-1}, a_n$. All spreadsheets provide the functions **COVAR** and **VAR**. **Oleo** does not provide any native function for computing the first-order autocorrelation or the covariance, and, therefore, was not assessed with respect to this quantity.

Table 4 concludes the analysis of univariate summary statistics with the results for the first-order autocorrelation coefficient. With the exception of **NumAcc1**, samples of low level of complexity are the ones that produce the worst results consistently across spreadsheets, versions

Datasets	Calc	Excel	Gnumeric	NeoOffice
	†/‡	2007/2008		2.2.5/3.0
Lew (l)	5.0	5.0	5.0	5.0
Lottery (l)	3.5	3.5	3.5	3.5
Mavro (l)	4.1	4.1	4.1	4.1
Michelso (l)	5.9	5.9/5.8	5.9	5.9
NumAcc1 (l)	15.0	15.0	15.0	15.0
PiDigits (l)	5.3	5.3	5.3	5.3
NumAcc2 (a)	14.4/15.0	11.3	15.0	11.5/15.0
NumAcc3 (a)	12.3	12.3/0.9	12.2	-/12.2
NumAcc4 (h)	11.0	11.0/NA	11.0	-/11.0

Table 4: *LREs* for the sample autocorrelation coefficient († Ubuntu versions, ‡ Mac OS and Windows versions).

and platforms. The smallest values of *LRE* are produced by **Excel** 2008 and **NeoOffice** 2.2.5 and, in particular, these spreadsheets did not return any correct digit for **NumAcc3** and **NumAcc4**.

The computation of the first-lag autocorrelation reveals differences among versions. Regarding **Excel**, it loses more than ten correct digits when switching from version 2007 to 2008 and using **NumAcc3** e **NumAcc4**. **NeoOffice** also presents differences of the same order in these same datasets, but the newer version is improved with respect to the older one.

Finally, **Calc** exhibits a small difference with respect to operating systems when computing the first-lag autocorrelation of **NumAcc2**: its Mac OS and Windows versions produce results of almost one more correct digit with respect to Ubuntu.

4.2. Analysis of variance

Only **Excel** 2007 and **Gnumeric** provide native functions for computing ANOVA, so the accuracy of its F statistic was only assessed for these two spreadsheets. We used **Analysis ToolPak** in **Excel**, and **ANOVA** in **Gnumeric**. Table 5 shows that both platforms achieved good results when low and average difficulty datasets are examined. We also observe that when they return different results, **Gnumeric** is better than **Excel** 2007. It is noteworthy that **Excel** 2007 produced an unacceptable result for the **SmLs09** dataset.

As for sample mean and standard deviation, **Excel** 2007 results for F statistic in ANOVA are in agreement with those reported by [McCullough and Wilson \(2005\)](#) and confirmed by [McCullough and Heiser \(2008\)](#).

4.3. Linear regression

Calc, **Excel**, **Gnumeric** and **NeoOffice** provide the **LINEST** function for linear regression in every version/platform here assessed. Table 6 presents the *LRE* values of the least accurate coefficient $\hat{\beta}$ and residual standard deviation (RSD) provided by each platform.

In the following tables, “NA” denotes situations for which no numeric answer is returned by

Datasets	Excel 2007	Gnumeric
SiRstv (l)	13.0	13.0
SmLs01 (l)	15.0	15.0
SmLs02 (l)	13.8	15.0
SmLs03 (l)	13.0	15.0
AtmWtAg (a)	10.1	10.1
SmLs04 (a)	10.4	10.4
SmLs05 (a)	10.2	10.2
SmLs06 (a)	10.1	10.1
SmLs07 (h)	4.1	4.4
SmLs08 (h)	1.8	4.1
SmLs09 (h)	–	4.1

Table 5: *LREs* for ANOVA *F* statistic.

Datasets	Calc [†]		Calc [‡]		Excel		Gnumeric	
	NeoOffice		2007/2008		1.8.3/1.9.1			
	$\hat{\beta}$	RSD	$\hat{\beta}$	RSD	$\hat{\beta}$	RSD	$\hat{\beta}$	RSD
Norris (l)	12.3	11.7	12.8	10.7	12.0	14.0	12.7	13.8/13.9
Pontius (l)	11.5	9.3	11.2	8.9	12.0	12.7	11.0	13.0/13.4
NoInt1 (a)	15.0	–	15.0	–	15.0	15.0	14.7	15.0
NoInt2 (a)	15.0	–	15.0	–	15.0	14.6	15.0	15.0/14.9
Filip (h)	–	NA	–	NA	7.2/6.4	7.2/6.4	0	0
Longley (h)	8.6	10.1	8.5	8.7	13.3	14.4	NA	NA
Wampler1 (h)	7.0	1.6	7.3	1.4	9.9	10.4	9.3	8.9
Wampler2 (h)	9.4	6.6	10.1	6.3	13.4	15.0	10.5	12.7
Wampler3 (h)	7.0	10.2	7.3	9.9	10.0	11.4	9.3	11.7
Wampler4 (h)	7.0	11.8	7.3	11.1	8.1	11.8	9.3	11.7
Wampler5 (h)	7.0	11.8	7.3	11.1	6.1	12.0	9.3	11.7

Table 6: *LREs* for the least accurate coefficient $\hat{\beta}$ and residual standard deviation (RSD).
[†] versions 2.4.1 and 3.0.1 for Ubuntu; [‡] **Calc** 3.0.1 for Windows and Mac OS, and also **Calc** 2.4.1 for Windows.

the spreadsheet; a “#NUM!” is placed in the cell where the result is expected, probably due to the fact that huge values are involved.

As Table 6 presents, regarding $\hat{\beta}$, **Excel** 2007 provides the best or equally good results in seven out of eleven datasets, and it is the only spreadsheet that provides (low-quality, with approximately only seven correct digits) results for the **Filip** dataset. **Excel** 2008 matches **Excel** 2007’s performance in all but one situation, namely for the **Filip** dataset, where the former misses about one digit with respect to the latter. **Excel** is outperformed by **Calc** 3.0.1 (Windows and Mac OS), **Calc** 2.4.1 (Windows) and **NeoOffice** when dealing with the low difficulty **Norris** dataset. **Gnumeric** is the best spreadsheet with two datasets that offer high

difficulty, namely `Wampler4` and `Wampler5`.

Regarding the RSD, as Table 6 presents, **Excel** 2007 produces the most accurate results (or as good results as other spreadsheets) in eight out of eleven situations. **Excel** 2008 matches **Excel** 2007's performance in all but the `Filip` dataset where, again, the former misses about one digit with respect to the latter. In the three situations where **Excel** is not the best platform, it is outperformed by **Gnumeric**; it happens with datasets having low, average and high difficulty.

[McCullough \(1998\)](#) suggests that at least nine correct digits should be expected in low-difficulty linear regression procedures.

As observed for sample mean, standard deviation and F statistic in ANOVA, **Excel** 2007 results for linear regressions match with those observed for [McCullough and Wilson \(2005\)](#) and confirmed by [McCullough and Heiser \(2008\)](#).

4.4. Nonlinear regression

Nonlinear regression was assessed with a suite of 27 datasets, transforming each regression into a nonlinear optimization problem, where the objective is minimizing the residual sum of squares. To achieve this, we used the general tool `Solver`.

The only spreadsheets that provide natively `Solver` with such capability are **Calc** 2.4.1 for Ubuntu, **Excel** 2007 and **NeoOffice** 2.2.5. The `Solver` from **Excel** 2007 provides two methods for solving nonlinear regression problems, namely Newton and Conjugate; they were both assessed.

By default, **Calc** 3.0.1 and **NeoOffice** 3.0 only provide a `Solver` for linear regression. An extension named `Solver for Nonlinear Regression` enabled the analysis on these spreadsheets. This extension can be found in the official site for extensions of **OpenOffice.org** (<http://extensions.services.openoffice.org/>), in a package provided by Sun Microsystems Inc. (who is also the holder of **OpenOffice.org Calc** copyright) under the LGPL license (for more information about this extension see <http://wiki.services.openoffice.org/wiki/NLPSolver>). This extension provides two non-deterministic evolutionary algorithms: DEPS and SCO.

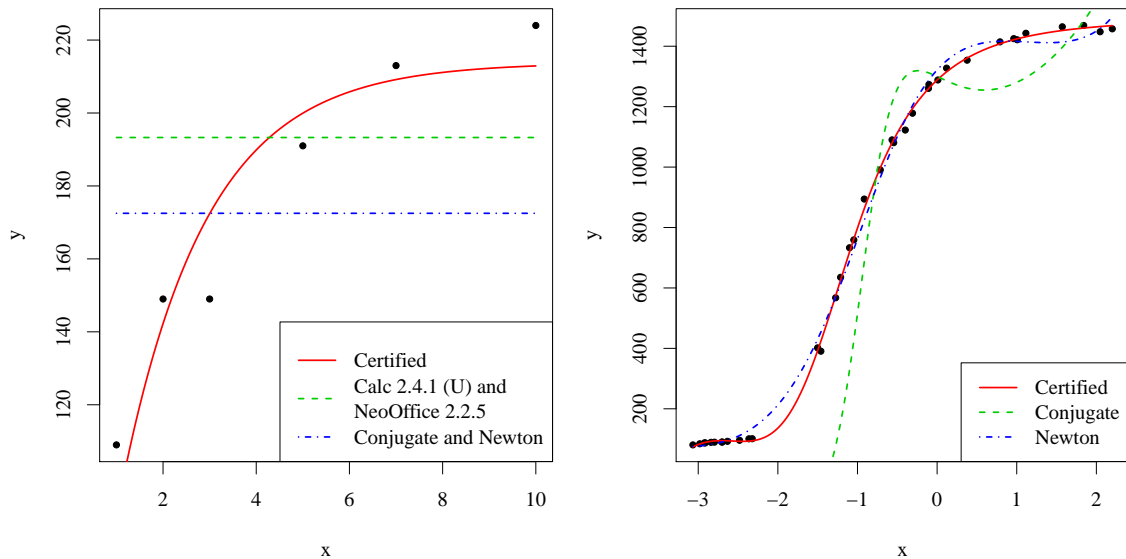
DEPS (differential evolution particle swarm) is a hybrid multiagent approach based on the particle swarm optimization paradigm ([Zhang and Xie 2003](#)), while SCO (social cognitive optimization) is based on social intelligence and human learning mechanisms ([Xie et al. 2002](#)).

Most algorithms considered here accept adjustments, despite loading with default parameters. Nevertheless, as [McCullough \(1998\)](#) comments, adjusting these settings may result in better solutions. In the following we assess these techniques with both the default parameters and sets chosen to improve results.

Nonlinear optimization procedures usually require starting points, and `Solver` is no exception. Each dataset is provided by NIST with two starting points: the first (denoted 'Start 1' in Tables 7 and 9) is far from final solution and it represents the usual situation where the user has no prior idea as to where the solution is. The second (denoted 'Start 2' in Tables 8 and 10) is closer to final solution.

Using default settings

This situation describes the user who has no prior idea about both the problem, its solution



(a) BoxBOD dataset from Start 2 in **Calc** 2.4.1 for **Ubuntu**, **NeoOffice** 2.2.5 and **Excel** 2007 (b) **Thurber** dataset from start 2 in **Excel** 2007

Figure 1: Nonlinear regressions for “–” results.

and the algorithm. None of the available settings was changed.

Tables 7 and 8 present the *LRE* of the least precise estimated coefficient in the regression; their sparseness clearly depicts how difficult this class of problems is for spreadsheets. In these tables ‘(M)’, ‘(U)’ and ‘(W)’ denote the operating system, i.e., Mac OS, Ubuntu and Windows.

Situations in which negative *LRE* values were obtained are denoted “–”. In order to illustrate the meaning of this notation, Figure 1 presents two examples from Table 8, which use Start 2. Figure 1a shows the results of fitting the BoxBOD dataset with the model $y = \beta_1(1 - \exp\{-\beta_2 x\}) + \varepsilon$; the curves show the results of using the certified values and those obtained with **Calc** 2.4.1, **NeoOffice** 2.2.5, Conjugate and Newton in **Excel** 2007. Clearly, these last results are meaningless, and their entries are denoted “–” in the Table. Figure 1b shows the Thurber dataset explained by the model

$$y = \frac{\beta_1 + \beta_2 x + \beta_3 x^2 + \beta_4 x^3}{1 + \beta_5 x + \beta_6 x^2 + \beta_7 x^3} + \varepsilon,$$

with the certified values and with those obtained by the Newton and Conjugate algorithms. Although the estimates obtained by the Newton algorithm present negative *LRE* values, cf. Table 8, the fit is not too bad visually. On the other hand, the Conjugate algorithm does not provide a satisfactory solution. Again, both entries are denoted “–”.

From Start 1 and 2, cf. Tables 7 and 8 respectively, we observe that sixteen and eighteen out of twenty-seven datasets, present at least four correct significant digits. According to McCullough (1998), these *LRE* values are reasonable results for nonlinear regressions. In a general manner, Start 2 presents better *LRE* values than Start 1, as expected.

Datasets	Calc 2.4.1 (U)	Calc 3.0.1 – DEPS (M)	Calc 3.0.1 – SCO (M)	Calc 3.0.1 – DEPS (U)	Calc 3.0.1 – SCO (U)	Calc 3.0.1 – DEPS (W)	Calc 3.0.1 – SCO (W)	Excel 2007 – Conjugate	Excel 2007 – Newton	NeoOffice 2.2.5	NeoOffice 3.0 – DEPS	NeoOffice 3.0 – SCO
Misra1a (l)	0	0	0	0	0	0	0	–	1.6	–	0	0
Chwirut2 (l)	–	5.6	4.4	4.8	4.9	6.1	5.0	0	4.3	0	5.4	4.8
Chwirut1 (l)	–	5.1	5.1	5.1	4.8	4.9	4.5	1.7	4.0	0	5.5	4.4
Lanczos3 (l)	–	0	–	0	–	0	–	–	–	–	–	–
Gauss1 (l)	0	5.7	6.1	5.8	5.9	6.0	5.7	1.0	4.8	0	6.1	5.8
Gauss2 (l)	0	5.8	–	6.1	–	5.9	5.3	1.3	4.6	0	5.9	–
DanWood (l)	1.1	4.3	4.1	4.7	5.0	4.6	4.2	4.0	4.7	1.0	4.2	4.8
Misra1b (l)	0	4.8	4.9	5.7	4.8	5.3	5.3	0	0	0	5.1	5.6
Kirby2 (a)	0	4.6	0	4.7	0	4.4	0	0	0	0	4.7	0
Hahn1 (a)	–	4.1	–	3.6	–	3.0	–	–	–	–	3.1	–
Nelson (a)	–	–	–	–	–	–	–	–	–	–	–	–
MGH17 (a)	–	–	–	0	–	–	–	–	–	–	–	–
Lanczos1 (a)	–	0	–	–	–	0	–	–	–	–	–	–
Lanczos2 (a)	–	–	–	–	–	–	–	–	–	–	0	–
Gauss3 (a)	0	5.9	–	6.0	–	6.1	3.0	0	4.3	0	5.4	0
Misra1c (a)	–	5.4	5.3	5.5	4.9	5.3	5.2	0	2.5	–	4.8	4.9
Misra1d (a)	0	6.0	4.5	5.9	4.6	4.7	5.4	0	1.0	–	5.0	4.6
Rozzman1 (a)	–	2.2	1.2	1.5	1.3	2.1	1.2	–	–	0	2.0	2.0
ENSO (a)	–	–	3.0	–	–	–	–	2.1	3.4	–	4.2	3.5
MGH09 (h)	–	–	–	–	–	–	–	–	–	–	–	–
Thurber (h)	0	5.8	0	5.8	0	6.1	0	–	1.3	0	6.6	0
BoxBOD (h)	–	–	–	–	–	–	–	–	–	–	–	–
Rat42 (h)	–	5.6	5.7	5.6	5.2	5.2	5.9	0	5.9	–	5.7	5.8
MGH10 (h)	–	6.5	–	6.7	–	6.1	–	–	–	–	6.2	–
Eckerle4 (h)	–	3.8	3.3	3.8	3.7	3.9	4.6	–	–	–	3.4	4.0
Rat43 (h)	–	–	–	–	–	–	–	–	–	0	–	–
Bennett5 (h)	–	0	0	2.8	0	0	0	0	0	0	0	0

Table 7: *LREs* for non-linear regression from Start 1, default parameters.

Results obtained from Start 1 can be analyzed according to the dataset complexity. Within low difficulty, for all but two datasets there are good results presented by at least one algorithm; no algorithm computes reliable values for **Misra1a** and **Lanczos3** datasets. Moreover, **Chwirut2**, **Chwirut1**, **Gauss1**, **Gauss2** and **Misra1b** dataset are difficult for Conjugate (**Excel 2007**). **Calc 2.4.1** and **NeoOffice 2.2.5** presented no reliable values in any dataset. As Table 7 shows, the best results are obtained with DEPS algorithm, regardless the spreadsheet

Datasets	Calc 2.4.1 (U)	Calc 3.0.1 – DEPS (M)	Calc 3.0.1 -SCO (M)	Calc 3.0.1 -DEPS (U)	Calc 3.0.1 – SCO (U)	Calc 3.0.1 – DEPS (W)	Calc 3.0.1 – SCO (W)	Excel 2007 – Conjugate	Excel 2007 – Newton	NeoOffice 2.2.5	NeoOffice 3.0 – DEPS	NeoOffice 3.0 – SCO
Misra1a (l)	1.3	5.3	5.0	5.4	5.2	5.9	6.2	1.3	1.3	–	6.1	5.8
Chwirut2 (l)	0	5.8	5.1	5.1	5.1	5.6	5.1	1.0	4.7	1.3	5.3	4.8
Chwirut1 (l)	–	5.7	4.7	5.4	5.6	5.1	5.0	1.0	4.9	0	5.7	4.9
Lanczos3 (l)	–	–	–	–	–	–	–	–	–	–	–	–
Gauss1 (l)	1.1	6.0	5.7	5.8	5.5	5.8	6.0	1.4	4.6	1.1	6.1	6.0
Gauss2 (l)	0	5.9	–	5.9	0	5.7	0	0	4.5	0	5.9	0
DanWood (l)	3.4	4.1	4.0	4.8	5.1	4.7	4.6	5.1	4.8	1.9	4.7	4.3
Misra1b (l)	0	5.2	5.3	5.3	5.2	5.5	6.0	0	2.8	0	5.3	5.7
Kirby2 (a)	0	4.6	–	4.7	–	4.0	–	0	0	0	4.5	0
Hahn1 (a)	0	3.6	–	3.1	–	3.7	0	–	–	0	3.7	–
Nelson (a)	–	2.9	2.3	3.6	2.6	3.0	2.3	0	0	0	3.2	3.5
MGH17 (a)	0	1.2	0	1.3	0	1.1	0	0	0	0	1.2	0
Lanczos1 (a)	–	–	–	–	–	–	–	–	–	–	–	–
Lanczos2 (a)	–	–	–	–	–	–	–	–	–	–	–	–
Gauss3 (a)	0	6.0	2.9	5.8	–	5.7	0	0	4.4	0	5.8	0
Misra1c (a)	1.2	5.7	5.3	5.7	5.4	5.4	5.4	1.1	1.2	1.1	5.9	5.1
Misra1d (a)	0	5.0	4.7	5.5	5.4	5.5	5.5	1.5	1.5	1.5	5.5	6.0
Roszman1 (a)	0	1.9	0	1.7	2.2	1.7	0	0	0	0	2.5	1.2
ENSO (a)	–	1.2	1.2	1.2	1.2	1.2	–	2.5	3.4	–	1.2	–
MGH09 (h)	–	1.8	0	1.7	1.3	1.8	1.5	1.1	4.3	–	1.7	0
Thurber (h)	0	6.2	1.3	5.8	1.0	5.7	0	–	–	0	6.0	1.2
BoxBOD (h)	–	5.9	6.7	6.2	6.0	6.9	5.7	–	–	–	5.9	5.5
Rat42 (h)	–	5.9	5.0	5.4	5.1	5.7	5.6	1.2	5.2	–	5.7	5.5
MGH10 (h)	–	5.8	0	6.8	0	7.1	1.5	–	–	–	6.0	–
Eckerle4 (h)	0	4.0	3.8	3.7	3.7	3.8	3.4	5.1	4.7	0	3.8	3.7
Rat43 (h)	–	5.7	2.3	5.2	2.0	5.3	3.9	2.1	3.5	1.3	5.2	2.3
Bennett5 (h)	–	0	0	0	1.2	0	0	0	0	0	0	1.1

Table 8: *LREs* for non-linear regression from Start 2, default parameters.

and operating system in which it is available. SCO also presents good results, except for **Gauss2** dataset in Ubuntu and Mac OS.

Still within low difficult datasets, but using Start 2, only **Lanczos3** dataset did not produce reliable estimates, producing negative *LRE* values in all spreadsheets, as shown in Table 8. In this table, **Misra1a** presents better *LREs* than with Start 1, however **Calc 2.4.1**, Conjugate, Newton and **NeoOffice 2.2.5** produce no reliable values. As for Start 1 results, Conjugate,

Calc 2.4.1 and **NeoOffice 2.2.5** achieved the worst accuracy. Again the best results are produced by the DEPS algorithm. The SCO algorithm produces no improvement when dealing with the **Gauss2** dataset. Moreover, its Windows version led to a worse result than the respective in Start 1.

Analyzing average difficult datasets, we found many problems in Start 1. **Nelson**, **MGH17**, **Lanczos1**, **Lanczos2** and **Roszman1** represent a great challenge for all algorithms herein assessed, and no reliable values were achieved. For the rest of datasets, DEPS achieved the best results, even for **ENS0** for which DEPS is the only one to present an acceptable *LRE*. **Calc 2.4.1**, Conjugate and **NeoOffice 2.2.5** could not deal with any dataset with good results and Newton did it only for **Gauss3**.

Regarding the use of Start 2, for average difficult datasets, Table 8 shows significative improvements for **Nelson**, **MGH17** and **Roszman1**, however these do not represent reliable answers. Furthermore the results for **Lanczos1** and **Lanczos2** are even worse than the ones obtained from Start 1. Due to the nondeterministic nature of DEPS and SCO algorithms, there is not enough evidence to state that improvements were achieved using Start 2. DEPS presents, nevertheless, the best *LRE* values. The poor performance of **Calc 2.4.1**, Conjugate, Newton and **NeoOffice 2.2.5**, observed from Start 1, does not improve significantly when switching to Start 2. As DEPS, SCO algorithm presents reliable results for some datasets, but it fails estimating parameters correctly for **Kirby2**, **Hahn1**, and **Gauss3**.

Focusing the analysis on highly difficult datasets, we observe from Table 7 that using Start 1 leads to no correct significant digit with any algorithm for **MGH09**, **BoxBOD** and **Rat43**. **Bennett5** also represents a very difficult situation for all algorithms, and no reliable results were observed. Almost reasonable results for **Ecker1e4** can be computed only by DEPS and SCO. In the rest of datasets, the best results are obtained with DEPS and SCO, in that order.

As Table 8 shows, many improvements were obtained using Start 2. The most noticeable change was reached for **BoxBOD** dataset. Here, from negative *LRE* values achieved from Start 1, reliable results were computed with DEPS and SCO algorithms using Start 2. Regarding DEPS only, this also happens for **Rat43**. Newton presents improvements related to **MGH09** and **Ecker1e4** datasets.

For any dataset complexity, there are situations for which no algorithm is able to compute reliable results using the default algorithm parameters. DEPS presents, nevertheless, the best *LRE* values for almost all comparisons regarding nonlinear regression when using default settings.

Customizing Solver settings

The blind use of default settings, though highly undesirable, is often found in practice. For instance, **Knight (2002)** and **Kaiser (2002)** report erroneous results obtained by pollution researchers in North America and Europe, when using default settings in a regression model. They report the problem as a software glitch, when, in fact, it is not. We emphasize that there is no safety in using the default settings when applying regressions, especially nonlinear regressions.

In the following, we present the assessment of nonlinear regressions with customized settings. Each Solver has its own parameters, according to the algorithm used, so it is not possible to discuss a single set of parameters; parameters identified as having similar effect were set equal. Speed was not considered in the performance of the algorithms, only the numerical

accuracy.

Firstly, we consider the parameters which are common to the two nonlinear algorithms available for **Excel**. In order to avoid, as much as possible, time or iterations limits we used 32,767 seconds for `max time` (upper bound available by the software) and 2,000 as upper bound for `iterations`. The `convergence` was set to $1E - 8$ and, as recommended by this **Solver** documentation, we chose *forward derivatives* and *tangent estimates*. The rest of the parameters were kept as default.

Secondly, we customized the DEPS and SCO algorithms. `Size of swarm` and `stagnation limit` were set to 150. Bigger values were tested, but no *LRE* improvements were observed. The `stagnation tolerance` has an analogy with the `tolerance` parameter of **Excel**, and then we used the same value in both cases, namely $1E - 8$. Again, all other parameter were kept as default.

Calc 2.4.1 and **NeoOffice 2.2.5** do not appear in this analysis because they are not customizable. Following the strategy conducted with the default settings, we present in Tables 9 and 10 the *LRE* of the least precise estimated coefficient in each regression. Once again, we used ‘(M)’, ‘(U)’ and ‘(W)’ in these tables to denote the operating system.

In a general manner, from Start 1 and 2, the algorithms with customized parametrization yielded better results than those obtained with default settings. Tables 9 and 10 show that, from Start 1 and 2, twenty and twenty-three respectively of twenty-seven datasets satisfied the four correct significant digits of accuracy requested by the McCullough (1998) criterion.

As Table 9 shows, reasonable *LRE* values were obtained for low difficulty datasets, with the exception of **Misra1a** and **Gauss2**. We highlight that Newton is the only algorithm that dealt with these two datasets in a satisfactory way. DEPS algorithm obtained good *LRE* values for **Gauss2** as well.

Lanczos3 is the only low difficulty dataset for which no significant digits were reached from Start 1 by any algorithm herein assessed.

Observing results achieved for low difficulty datasets from Start 2 in Table 10, we note that we better *LRE* values are obtained when compared with Start 1. Only problems with **Lanczos3** dataset were observed.

A common issue from Start 1 and 2 is the poor precision obtained by the SCO algorithm. The biggest *LRE* values were obtained with the Newton algorithm for both starting points. DEPS is more robust than the rest of algorithms, as can be seen in Tables 9 and 10.

Regarding average difficulty datasets, we note from Table 9 that three out of eleven datasets do not present satisfactory *LRE* values in the Start 1 case: **MGH17**, **Lanczos1** and **Lanczos2** (these two last did not produce a single correct digit). Though the overall results are improved with respect to those obtained without parameter tuning, cf. Table 7, they are still not reliable enough; only **Misra1c** e **Misra1d** produce acceptable results, within these datasets, in eight and nine, respectively, of the situations. Best results are obtained by DEPS and Newton.

Considering Start 2 in Table 10, we still observe problems in **Lanczos1** and **Lanczos2** datasets. Concerning all datasets but these two, we obtained satisfactory results for six out of eleven datasets using DEPS algorithm, and six out of eleven using Newton. SCO algorithm reached acceptable results for three of these cases, and Conjugate only for two of them.

With regard to high difficult datasets, we observe that for Start 1 we get reliable results in five out of eight datasets (see Table 9). DEPS algorithm deals correctly with four of these

Datasets	Calc 3.0.1 – DEPS (M)	Calc 3.0.1 – SCO (M)	Calc 3.0.1 – DEPS (U)	Calc 3.0.1 – SCO (U)	Calc 3.0.1 – DEPS (W)	Calc 3.0.1 – SCO (W)	Excel 2007 – Conjugate	Excel 2007 – Newton	NeoOffice 3.0 – DEPS	NeoOffice 3.0 – SCO
Misra1a (l)	0	0	0	0	0	0	–	4.5	0	0
Chwirut2 (l)	6.3	6.3	6.4	5.6	5.8	6.0	4.6	7.0	6.8	6.2
Chwirut1 (l)	6.6	6.3	6.4	6.8	6.6	7.3	4.4	7.1	6.8	6.2
Lanczos3 (l)	0	–	0	–	0	–	–	–	–	–
Gauss1 (l)	7.0	7.1	6.7	6.7	6.7	7.0	4.0	7.6	6.9	6.7
Gauss2 (l)	7.0	–	7.0	–	6.8	–	3.6	7.5	7.2	–
DanWood (l)	5.7	5.8	6.5	6.3	5.3	4.8	9.1	9.8	6.2	5.7
Misra1b (l)	6.1	5.6	5.9	6.3	6.5	5.8	0	5.6	6.5	5.7
Kirby2 (a)	5.2	0	5.3	0	5.3	0	0	0	5.1	0
Hahn1 (a)	4.7	0	4.8	–	5.0	–	–	–	4.7	–
Nelson (a)	–	–	–	–	–	–	0	4.8	–	–
MGH17 (a)	3.1	–	–	–	3.5	–	–	–	3.1	–
Lanczos1 (a)	0	–	0	–	0	–	–	–	0	–
Lanczos2 (a)	0	–	0	–	0	–	–	–	0	–
Gauss3 (a)	6.8	–	–	–	6.5	0	2.4	7.6	6.8	–
Misra1c (a)	5.9	6.0	8.0	6.0	7.0	5.9	0	2.9	5.9	6.0
Misra1d (a)	7.5	6.0	6.3	7.5	6.3	6.2	0	4.0	7.5	6.1
Rozzman1 (a)	3.2	1.2	2.6	1.3	2.7	1.5	–	9.1	3.2	9.0
ENSO (a)	–	–	–	–	–	–	5.8	7.3	–	–
MGH09 (h)	–	–	–	–	–	–	–	–	–	–
Thurber (h)	7.0	0	7.1	0	7.0	0	–	7.4	7.0	0
BoxBOD (h)	–	–	–	–	–	–	8.7	9.0	–	–
Rat42 (h)	6.2	6.7	6.2	6.2	6.5	6.1	4.8	8.4	6.2	6.0
MGH10 (h)	7.1	–	7.0	–	7.3	–	–	–	7.1	–
Eckerle4 (h)	5.0	4.8	4.9	5.1	4.7	4.9	–	–	5.0	4.8
Rat43 (h)	–	–	–	–	–	–	–	–	–	–
Bennett5 (h)	0	0	0	0	1.7	0	0	0	0	–

Table 9: *LREs* for customized non-linear regression from Start 1

datasets, and Newton reached satisfactory *LRE* values for three of them. Both SCO and Conjugate algorithms have problems with all but two datasets.

Additionally, we observe big differences between Start 2 and Start 1 (see Tables 9 and 10). The only one dataset from Start 2 for which there are problems is **Bennett5**. The best results in this case were found with DEPS algorithm, which reached reasonable results for six of eight datasets. On the other hand, Newton obtained satisfactory *LRE* values for five of these high

Datasets	Calc 3.0.1 – DEPS (M)	Calc 3.0.1 – SCO (M)	Calc 3.0.1 – DEPS (U)	Calc 3.0.1 – SCO (U)	Calc 3.0.1 – DEPS (W)	Calc 3.0.1 – SCO (W)	Excel 2007 – Conjugate	Excel 2007 – Newton	NeoOffice 3.0 – DEPS	NeoOffice 3.0 – SCO
Misra1a (l)	6.0	6.0	6.1	5.9	6.5	6.3	1.3	4.3	6.7	6.6
Chwirut2 (l)	6.3	6.0	5.9	5.5	6.3	6.2	3.5	7.0	6.2	6.1
Chwirut1 (l)	6.2	6.4	7.1	6.3	6.9	6.6	4.9	7.0	6.2	6.4
Lanczos3 (l)	–	–	–	–	–	–	–	–	–	–
Gauss1 (l)	7.1	6.9	7.1	7.3	7.0	7.2	4.3	7.6	6.7	6.7
Gauss2 (l)	7.2	–	7.1	–	7.2	–	3.6	7.5	7.2	6.8
DanWood (l)	5.6	5.2	5.7	4.9	6.0	5.3	9.0	9.4	5.3	5.7
Misra1b (l)	5.9	6.2	6.9	6.6	7.0	5.8	0	3.4	6.1	6.3
Kirby2 (a)	5.8	0	5.6	0	5.6	0	0	0	4.9	0
Hahn1 (a)	4.4	0	4.2	–	4.7	–	–	–	4.4	–
Nelson (a)	5.0	4.0	4.3	4.0	4.2	4.2	0	4.8	4.1	3.7
MGH17 (a)	3.5	0	1.2	0	3.1	0	0	4.4	3.5	0
Lanczos1 (a)	–	–	–	–	–	–	–	–	–	–
Lanczos2 (a)	–	–	1.1	–	–	–	–	–	–	–
Gauss3 (a)	6.7	3.6	6.4	0	7.0	–	2.9	7.8	6.7	–
Misra1c (a)	7.0	6.3	6.0	7.3	6.2	6.2	1.2	3.1	7.0	6.5
Misra1d (a)	6.4	6.6	6.5	5.8	6.7	6.6	1.5	3.3	6.4	6.6
Rozzman1 (a)	2.8	1.3	3.5	2.6	2.5	1.4	0	8.1	2.8	1.4
ENSO (a)	1.2	–	1.2	1.2	1.2	1.2	6.2	6.5	1.2	–
MGH09 (h)	2.7	2.3	2.5	2.3	2.6	2.4	3.4	5.0	2.7	2.0
Thurber (h)	6.5	0	6.8	0	6.8	0	0	7.2	6.5	0
BoxBOD (h)	7.4	7.4	7.1	7.1	7.3	8.0	–	–	7.4	6.9
Rat42 (h)	6.5	6.9	6.7	6.5	6.1	6.7	6.2	8.5	6.5	6.7
MGH10 (h)	7.9	–	7.2	–	7.3	–	–	1.4	7.9	–
Eckerle4 (h)	4.7	4.7	–	4.7	4.9	4.8	6.2	5.9	4.7	5.1
Rat43 (h)	6.4	4.2	7.1	4.3	7.1	4.6	3.7	8.9	6.4	4.9
Bennett5 (h)	1.2	0	1.4	0	0	0	0	0	1.2	1.5

Table 10: *LREs* for customized non-linear regression from Start 2.

difficulty datasets. We remark that the worst results were reached applying the Conjugate algorithm.

An overview of the three kinds of datasets complexity shows that we get improved *LRE* values when using Start 2. This issue lead to assert that almost all algorithm take advantage of closer initial points, as expected.

	Calc	Excel 2007	Excel 2008	Gnumeric	NeoOffice	Oleo
Documentation	N	Y-wrong	N	Y	N	N
Seed	N	Y	N	N	N	N

Table 11: Documentation and seed availability of pseudorandom number generators.

Results achieved with customized settings from Start 2 are roughly the upper bound of reliability that we can get using spreadsheets as nonlinear solvers.

A third starting point was also used with customized parameters: the certified value. It is useful to assess the algorithm’s ability to identify when it has reached the solution. Conjugate and Newton (available in **Excel**) recognized when the current solution is optimal in all but with the **Bennett5** dataset. DEPS (from **Calc** and **NeoOffice**) fails more often: 12, 13 and 9 times out of 27 datasets, in Windows, Mac OS and Ubuntu, respectively. It is noteworthy, though, that even failing to stop at the certified value, DEPS provides at least $LRE = 7$ in all datasets but **Rat43**, for which negative LRE values were obtained, and **Bennett5**, where one significant correct digit was computed.

4.5. Pseudorandom number generation

According to Ripley (1987, 1990) good pseudorandom number generators ought to provide sequences of numbers with the following properties:

1. they resemble outcomes from uniformly-distributed random variables,
2. vectors of moderate dimensions of those random variables are collectively independent,
3. repeatability from a few easily to specify parameters, the seed, in a wide variety of computational environments (hardware, operating system, programming language),
4. speed,
5. long periods.

Verifying the two first properties for a given sequence is tough, and a number of tests has been proposed in the literature. Marsaglia’s Diehard tests (Marsaglia 1995) and the NIST Random Number Generation standard (Rukhin *et al.* 2008) are some of the tools available for such assessment.

From the user viewpoint, good documentation that may lead to informed decisions would suffice. Table 11 presents a summary of the documentation and setting seed availability of all the spreadsheets under assessment.

Calc’s documentation provides no information about the algorithm implemented and provides no user function for setting the seed. The source code claims that it uses the C rand function (which has no default implementation specified in the ISO C standard – ISO/IEC 9899:TC2) in its RNG. The only information is that the function generates numbers between 0 and, at least, 32767. Therefore according to the implementation adopted into the library (`stdlib.h`) used to compile it, a new RNG may be produced yielding, thus, a non-portable function.

NeoOffice, which is based on **OpenOffice.org**, suffers from the same issue. From the user’s perspective, **Gnumeric** does not provide any high-level means for setting the seed of the random number generator. The generator implemented by **Gnumeric** is the long-period Mersenne-Twister (Matsumoto and Nishimura 1998).

Microsoft claims that **Excel** 2003 and 2007 use an implementation of the Wichmann and Hill (1982) algorithm, but as shown by McCullough (2008a) this is not true. The same methodology was applied to **Excel** 2008, and we also concluded that whichever the algorithm implemented, it is neither the original Wichman-Hill nor the new version (Wichmann and Hill 2006). The Mac OS version does not provide any information about this implementation.

Oleo provides an undocumented function for the generation of integer values in the range $0, \dots, x$, with x provided by the user. The only information about this function is available in **Oleo**’s source code, and states that a “linear feedback shift register” is used. Once entered the command, the value is updated regularly at intervals from 1 to 10 seconds, at the user’s choice. There is no high-level access to the seed.

4.6. Distribution functions

According to Knüsel (1995) the answer given by a program should be correct and reliable as it is printed out. Furthermore, according to Yalta (2008), good statistical software should be able to provide six or seven accurate digits for probabilities as small as 10^{-100} .

Yalta (2008) presents a detailed assessment of the numerical issues that different versions of **Excel**, versions from 97 to 2007, exhibit in statistical distributions. The author analyzes Microsoft’s performance on correcting errors reported in the literature, and compares its spreadsheet with **Gnumeric** 1.7.11 and **Calc** 2.3.0. No information about assessments on **NeoOffice** were found in the literature, to the best of our knowledge.

In this section we present the numerical accuracy of the main statistical distributions assessed by Yalta (2008), but restricted to those situations where difficulties were observed. With this approach we put in evidence the differences between the spreadsheets herein assessed.

The specific name and parameters of functions are the same in all platforms and versions. **Gnumeric** provides another sets of functions based on the R platform (Almiron *et al.* 2009). We tested both sets, and no differences were observed in their numerical precision. **Oleo** was not assessed since it does not provide native resources for computing distribution functions.

The function `BINOMDIST(k, n, p, cum = 1)` computes the probability $P\{X \leq k\}$, where X follows a binomial distribution with n trials and p the probability of success on each trial. In **Gnumeric**, the R-based function `R.PBINOM(k, n, p)` can be used for the same purpose. Table 12 shows that, for $n = 1030$ and $p = 0.5$, **Excel** 2007 cannot compute any digit correctly for $k \in \{1, 2, 100, 300\}$, whereas **Calc**, **Excel** 2008, **NeoOffice** and **Gnumeric**, provide good accuracy in all tested cases, including those in which probabilities are much smaller than 10^{-100} .

`POISSON(k, lambda, cum)` computes $P\{X \leq k\}$ if $cum = 1$, and $P\{X = k\}$ if $cum = 0$, where X follows a Poisson distribution with mean $\lambda > 0$. **Gnumeric**’s R-based functions `R.PPOIS(k, lambda)` and `R.DPOIS(k, lambda)`, for $cum = 1$ and $cum = 0$, respectively, can be used as well. For Poisson probabilities, we observe in Table 13 that, again, **Excel** presents the worst results, while **Calc**, **Gnumeric** and **NeoOffice**, offer excellent accuracy. When computing the cumulative distribution function, **Excel** is unable to compute any digit

k	Certified $P\{X \leq k\}$	Calc	
		Excel 2008	
		NeoOffice	Excel 2007
1	$8.96114E - 308$	6.0	0
2	$4.61499E - 305$	6.0	0
100	$1.39413E - 169$	5.5	0
300	$2.91621E - 42$	6.0	0
400	$3.89735E - 13$	6.0	2.1
410	$3.19438E - 11$	5.8	4.0

Table 12: *LREs* for the binomial distribution with $n = 1030$ and $p = 0.5$.

k	λ	Certified $P\{X = k\}$	Calc		
			NeoOffice	Excel	Gnumeric
0	200	$1.38390E - 87$	5.6	0	5.6
103	200	$1.41720E - 14$	6.0	0	6.0
315	200	$1.41948E - 14$	6.0	0	6.0
400	200	$5.58069E - 36$	6.0	0	6.0
900	200	$1.73230E - 286$	6.0	0	6.0

k	λ	Certified $P\{X \leq k\}$	Calc		
			NeoOffice	Excel	Gnumeric
$1E + 05$	$1E + 05$	0.500841	NA	0	6.0
$1E + 07$	$1E + 07$	0.500084	NA	0	6.0
$1E + 09$	$1E + 09$	0.500008	NA	0	6.0

Table 13: *LREs* for the Poisson distribution.

correctly, while **Calc** and **NeoOffice** do not return any numeric answer avoiding, thus, to mislead the users. Exact results can be computed with **Gnumeric**.

The function `GAMMADIST(x, alpha, beta, cum)` computes $P\{X \leq x\}$ if $cum = 1$, and the density at x if $cum = 0$, with X following a gamma distribution with shape α and scale β . Alternatively, **Gnumeric**'s R-based functions are `R.PGAMMA(x, alpha, beta)` and `R.DGAMMA(x, alpha, beta)`, for $cum = 1$ and $cum = 0$, respectively. As Table 14 shows, **Calc**, **NeoOffice** and **Gnumeric** present exact answers for all cases of cumulative distribution functions. **Excel** also presents good results except for $x = 0.1$, where no numerical answer is provided.

If X follows a standard Gaussian distribution, then `NORMSINV(p)` computes the value of x such that $P\{X \leq x\} = p$, i.e., the p -quantile. **Gnumeric** offers the alternative R-based function `R.QNORM(p, 0, 1)`. Table 15 shows that **Excel** has serious problems for values of $p < 10^{-198}$, whereas **Calc**, **NeoOffice** and **Gnumeric** return exact answers whenever $p \geq 10^{-300}$.

If X obeys a χ^2 distribution with n degrees of freedom, then the function `CHIINV(p, n)` computes the value of x such that $P\{X > x\} = p$. Alternatively, the **Gnumeric**'s R-based

x	α	Certified $P\{X \leq x\}$	Calc	
			NeoOffice Gnumeric	Excel
0.1	0.1	0.827552	6.0	NA
0.2	0.1	0.879420	6.0	6.0
0.2	0.2	0.764435	6.0	5.9
0.4	0.3	0.776381	6.0	6.0
0.5	0.4	0.748019	6.0	6.0

Table 14: *LREs* for the gamma distribution with $\beta = 1$.

p	Certified p -quantile	Calc	
		NeoOffice Gnumeric	Excel
$5E - 1$	0	6.0	6.0
$1E - 198$	-30.0529	6.0	2.8
$1E - 300$	-37.0471	6.0	0

Table 15: *LREs* for the standard Gaussian distribution.

p	n	Certified x such that $P\{X > x\} = p$	Calc 2.4.1	Calc 3.0.1	
			NeoOffice 2.2.5	NeoOffice 3.0	Excel
$2E - 1$	1	1.64237	5.6	5.6	5.5
$1E - 7$	1	28.3740	2.2	6.0	NA
$1E - 7$	5	40.8630	2.7	6.0	NA
$1E - 12$	1	50.8441	1.3	6.0	NA
$1E - 12$	5	65.2386	-	6.0	NA
0.48	778	779.312	6.0	6.0	NA
0.52	782	779.353	6.0	6.0	NA

Table 16: *LREs* for the χ^2 distribution.

function `R.QCHISQ(p, n, 0)` can be used as well. From Table 16 we notice that for small values of p or large degrees of freedom, **Excel** does not return any numeric value. **Calc** 2.4.1 and **NeoOffice** 2.2.5 offer bad results for small values of p . **Calc** 3.0.1, **Gnumeric** and **NeoOffice** 3.0 present noticeable improvements; they are able to compute the exact values for all the cases assessed except for one, in which the accuracy is almost exact (see Table 16).

If X has a beta distribution with parameters α and β , then `BETAINV(p, alpha, beta)` computes the value of x such that $P\{X \leq x\} = p$, i.e. the p -quantile. The R-based function in **Gnumeric** is `R.QBETA(p, alpha, beta)`. As Table 17 shows, for values of $p < 10^{-3}$ **Excel** is unreliable, while for $p < 10^{-8}$ it returns values very far from the correct answers (“-” denotes

p	Certified p -quantile	Calc 2.4.1	Calc 3.0.1 [†]	Calc 3.0.1 [‡]	Excel
		NeoOffice 2.2.5	NeoOffice 3.0	Gnumeric	
$1E - 2$	$2.94314E - 01$	6.0	6.0	6.0	5.3
$1E - 3$	$1.81386E - 01$	6.0	6.0	6.0	4.2
$1E - 4$	$1.12969E - 01$	5.4	5.4	5.4	3.2
$1E - 5$	$7.07371E - 02$	5.7	6.0	6.0	2.2
$1E - 6$	$4.44270E - 02$	5.4	6.0	6.0	1.4
$1E - 7$	$2.79523E - 02$	2.3	5.9	5.9	0
$1E - 8$	$1.76057E - 02$	1.2	6.0	6.0	0
$1E - 9$	$1.10963E - 02$	0	5.5	5.5	–
$1E - 10$	$6.99645E - 03$	0	6.0	6.0	–
$1E - 11$	$4.41255E - 03$	0	6.0	6.0	–
$1E - 12$	$2.78337E - 03$	0	5.9	5.9	–
$1E - 13$	$1.75589E - 03$	0	6.0	6.0	–
$1E - 100$	$6.98827E - 21$	0	–	6.0	–

Table 17: $LREs$ for the beta distribution with $\alpha = 5$ and $\beta = 2$ ([†] Mac OS version; [‡] Ubuntu and Windows versions).

p	Certified x such that $P\{X > x\} = p$	Calc 2.4.1	Calc 3.0.1 [†]	Calc 3.0.1 [‡]
		NeoOffice 2.2.5	Excel NeoOffice 3.0	Gnumeric
$1E - 8$	$3.18310E + 07$	NA	0	6.0
$1E - 11$	$3.18310E + 10$	NA	0	6.0
$1E - 12$	$3.18310E + 11$	NA	0	6.0
$1E - 13$	$3.18310E + 12$	NA	0	6.0
$1E - 100$	$3.18310E + 99$	NA	0	6.0

Table 18: $LREs$ for the t distribution with $n = 1$ ([†] Mac OS version; [‡] Ubuntu and Windows versions).

such situation). **Calc 2.4.1** and **NeoOffice 2.2.5** cannot compute accurately this distribution for values of p smaller than 10^{-6} . On the other hand, **Calc 3.0.1** for Mac OS and **NeoOffice 3.0** compute accurate answers for values of $p \geq 10^{-13}$. Finally, **Gnumeric** and **Calc 3.0.1** for Ubuntu and Windows presented reliable answers in all cases tested (values of $p \geq 10^{-100}$).

If X follows a Student's t distribution with n degrees of freedom, then `TINV(p, n, cum=1)` computes x such that $P\{|X| > x\} = p$. Since the certified values for this law are right-tailed probabilities, we computed `TINV(2p, n)`. This can be computed in **Gnumeric** with the R-based function `R.QT(p, n, 0)` as well. Table 18 shows that, for the cases analyzed, no accurate results can be obtained with **Calc 2.4.1**, **Calc 3.0.1** for Mac OS, **NeoOffice** and **Excel**. **Calc 2.4.1** and **NeoOffice 2.2.5** present the advantage that no numeric answer is given and, therefore, users are not misled. On the other hand, **Calc 3.0.1** for Ubuntu and Windows and **Gnumeric** provide exact answer for values of $p \geq 10^{-100}$.

p	Certified x such that $P\{X > x\} = p$	Calc 2.4.1	Calc 3.0.1 [†]	Calc 3.0.1 [‡] Gnumeric
		Excel 2008 NeoOffice 2.2.5	Excel 2007 NeoOffice 3.0	
$1E - 5$	$4.05285E + 09$	NA	0	6.0
$1E - 6$	$4.05285E + 11$	NA	0	6.0
$1E - 12$	$4.05285E + 23$	NA	0	6.0
$1E - 13$	$4.05285E + 25$	NA	0	6.0
$1E - 100$	$4.05285E + 199$	NA	0	6.0

Table 19: *LREs* for the F distribution with $n_1 = n_2 = 1$ ([†] Mac OS version; [‡] Ubuntu and Windows versions).

The function `FINV(p, n_1, n_2)` computes the value of x such that $P\{X > x\} = p$ for random variables following the $F(n_1, n_2)$ law. **Gnumeric**'s R-based function `R.QF(p, n_1, n_2, 0)` can be used with the same purpose. As Table 19 shows, almost all spreadsheets are unable to compute any digit correctly, except **Calc** 3.0.1 for Ubuntu and Windows and **Gnumeric**, which provide exact answers for all cases herein assessed. We observe once again that the cases where no numeric value is returned (as is the case of **Calc** 2.4.1, **Excel** 2008 and **NeoOffice** 2.2.5) are better than those in which an inaccurate answer is given. The worst results are those produced by **Calc** 3.0.1 for Mac OS, **Excel** 2007 and **NeoOffice** 3.0.

5. Concluding remarks and warnings

This work presented the assessment of well known spreadsheets widely used for statistical computing, among other applications. They were assessed in three areas: estimation, random number generation and statistical distributions.

Regarding univariate summary statistics, **Excel** 2008 and **NeoOffice** 2.2.5 are not able to compute first-lag autocorrelation consistently with acceptable precision, being **Gnumeric** the best choice for sample mean, standard deviation and first-order autocorrelation. **Oleo** should only be used when no other spreadsheet is available, e.g. when no windows system is at hand. If that is the case, the user should bear in mind that its precision is quite limited.

The only spreadsheets that offer a function for computing the F statistic in one-way ANOVA are **Excel** 2007 and **Gnumeric**. They gave accurate results in low and average difficult datasets, whereas for high difficult datasets they presented problems, with **Excel** 2007 providing worse results.

There is no single spreadsheet able to provide consistently good results when the measure of quality is the number of correct significant digits of the least precise coefficient in linear regression problems. **Excel** performs well except for **Wampler5**, for which it provides unacceptable results when compared with the ones computed by **Gnumeric**. **Calc** and **NeoOffice** provide acceptable results in most situations, but with serious problems for the **Filip** dataset. When the accuracy of RSD is the measure of quality, one may stick to **Excel** (mainly in its 2007 version) as the sole spreadsheet for linear regression.

Nonlinear regression was assessed in four situations: using the default settings and fine tuning

the parameters, with two starting points for each one, namely, close and far from the certified solution. Using the default settings and both starting points, though some algorithms presented good results in more than half datasets, serious problems were observed with the rest. The DEPS algorithm presented the best success/failure rate, but it did not produce reliable results in more than 30% of the cases; therefore, there is not enough evidence to advise its use for nonlinear regression. Moreover, **Calc** 2.4.1 and **NeoOffice** 2.2.5 should not be used for this purpose. **Calc** 2.4.1 and **NeoOffice** 2.2.5 do not provide means for adjusting the algorithms parameters, a major drawback for serious users. An overall better behavior is observed with tuned parameters, and differences are noticed between starting points. Regarding the remaining spreadsheets, at least one (two, resp.) digit(s) of accuracy for the first (second, resp.) starting point is (are) not achieved in only four datasets. DEPS again achieves the best results with more than 70% of reliable results, followed by Newton; Conjugate fails in more than 70% of the assessments, while SCO fails in more than 65% (50%, resp.) with the first (second, resp.) start point. When starting in the optimal solution, Conjugate and Newton fail only once in identifying that they already are at the solution. Therefore, there is still not enough evidence to advise their use for nonlinear regression, since they fail in almost 30% of the cases, in the best situations.

Whichever the spreadsheet and platform, issues regarding documentation and/or repeatability prevent their use in serious statistical procedures that employ simulation.

Concerning distribution functions, cases that pose difficulties, identified by Yalta (2008), were assessed. For all the situations **Gnumeric** achieved exact answers. Similarly, **Calc** 3.0.1 for Ubuntu and Windows achieved good precision, except for the Poisson cumulative distribution function. The binomial distribution should not be computed with **Excel** 2007. **Excel** has serious problems with the Poisson distribution, and its precision is limited for the standard Gaussian distribution. **Calc** 3.0.1, **NeoOffice** 3.0 and **Gnumeric** offer good results for the beta distribution. Only **Calc** 3.0.1 for Ubuntu and Windows and **Gnumeric** should be used for the t and F distributions.

There are some variations of LRE values in the same platforms when evaluated in different operating systems and architectures. However, those variations are not significative, with the exception of **Excel** 2008 and **Calc** 3.0.1 for Mac OS. The former presents improved LRE values for binomial distribution, but worse results when calculating the sample standard deviation. In **Calc** 3.0.1, the Mac OS version presents significantly worse results for t and F distributions than its Ubuntu and Windows versions.

On the other hand, improvements were observed for some distribution functions. **Calc** 3.0.1 and **NeoOffice** 3.0 enhanced their precision, when compared to previous versions, regarding the χ^2 and beta distributions.

Summarizing the main points herein discussed, it is not recommended to use any spreadsheet for nonlinear regression and/or Monte Carlo experiments. **Excel** incurs in the very same errors of older versions detected, among others, by McCullough (2008b); McCullough and Heiser (2008); McCullough (2004); Nash (2008). Nash (2008) claims that no spreadsheet should be used in classroom, especially for teaching statistics.

Concerning graphics production, McCullough and Heiser (2008) and Su (2008) argue that the default charts produced by **Excel** do not promote data comprehension, and may cause problems in their understanding. No assessment of the quality of charts produced by spreadsheets other than **Excel** was found in the literature, and this is a venue for future research.

Regarding costs, spreadsheets distributed under the terms of the GPL/LGPL, namely, **Calc**, **Gnumeric**, **NeoOffice** and **Oleo**, can be freely used and distributed. **Excel**'s license has to be purchased.

Finally, as a rule of the thumb, every user should be aware that spreadsheets have serious limitations. Other platforms are advisable, being currently R the most dependable FLOSS (Free/Libre Open Source Software, see [Almiron *et al.* 2009](#)).

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