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PLS Path Modeling – A Software Review

Dirk Temme*
Henning Kreis*
Lutz Hildebrandt*

* Institute of Marketing, Humboldt-Universität zu Berlin, Germany

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Dirk Temme, Henning Kreis and Lutz Hildebrandt
Institute of Marketing, Humboldt University Berlin
Spandauer Straße 1, 10099 Berlin
{temme, kreis, hildebr}@wiwi.hu-berlin.de

Abstract

After years of stagnancy, PLS path modeling has recently attracted renewed interest from applied researchers in marketing. At the same time, the availability of software alternatives to Lohmöller's *LVPLS* package has considerably increased *(PLS-Grap*h, *PLS-GU*I, *SPAD-PL*S, *SmartPL*S). To help the user to make an informed decision, the existing programs are reviewed; their strengths and weaknesses are identified. Furthermore, analyzing simulated data reveals that the signs of weights/factor loadings and path coefficients can vary considerably across the different programs. Thus, applied researchers should treat the interpretation of their results with caution. Compared to programs for analysis of covariance structure models *(LISREL* approach), PLS path modeling software is on equal footing regarding ease of use, but clearly lags behind in terms of methodological capabilities.

Keywords: PLS path modeling, Marketing, Formative indicators, Reflective indicators

JEL-Codes: C31, C87, M31

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Dirk Temme[1], Henning Kreis[2], and Lutz Hildebrandt[3]

[1] Institute of Marketing, Humboldt University Berlin, Spandauer Str. 1, 10099 Berlin, Germany, temme@wiwi.hu-berlin.de
[2] kreis@wiwi.hu-berlin.de
[3] hildebr@wiwi.hu-berlin.de

1 Introduction

When it comes to modeling relationships between latent variables, mainly two different methodological approaches can be distinguished: Covariance structure analysis on the one hand and PLS path modeling (not to be confused with PLS regression) on the other. Although both methods emerged roughly at the same time, their development took a rather diverse course. Since the introduction of the first LISREL version in the early 1970s, the software available for covariance structure analysis has experienced substantial progress with respect to ease-of-use and methodological capabilities. Graphical interfaces in programs like AMOS or LISREL have freed the user from having to specify his/her model in matrix or equation form. Simultaneously, estimation methods for non-normal/categorical data as well as multi-level, multi-group, and finite mixture models have emerged, thus offering a wide range of possible applications. Meanwhile, covariance structure analysis is arguably one of the most popular methods used in the social sciences (e.g., marketing).

In contrast, PLS path modeling has, until recently, rarely been applied in marketing although its basic algorithms were developed in the 1970s and the first software packages were publicly available in the 1980s (*LVPLS* (Lohmöller, 1984), PLSPath (Sellin, 1989)). The rather limited use of PLS path modeling in the last decades can be explained to a considerable degree by the lack of progress regarding the software's ease-of-use and methodological options. Recently, however, this situation has changed tremendously. Currently, researchers can choose between several alternative software solutions (*PLS-GUI*, *VisualPLS*, *PLS-Graph*, *SmartPLS*, *SPAD-PLS*) which provide a clear improvement especially in terms of user-friendliness. Furthermore, growing need in modeling so-called formative constructs, particularly in marketing and management/organizational research (e.g., Diamantopoulos and Winklhofer (2001), Jarvis et al. (2003), MacKenzie et al. (2005)), has stimulated great interest in applying the PLS path modeling approach. Although models with formative constructs can, in principle, also be estimated within covariance structure analysis (e.g., MIMIC models), doing so causes specific identification problems which are not an issue in PLS (e.g., MacCallum and Browne (1993)).

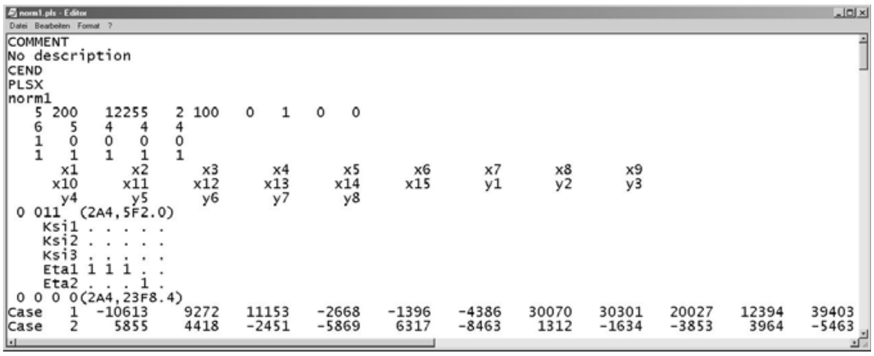
Against the background of a growing number of PLS software packages and an increasing differentiation in the programs' capabilities, a comprehensive review would help researchers to decide on the specific PLS program to be used in their studies. To the best of our knowledge, no such review of PLS path modeling software currently exists. In order to close this gap, we aim at providing an informative software overview by identifying specific strengths and weaknesses of the relevant programs. In the remaining part of the article, we offer a brief description of each software package; in addition, screenshots will give an impression of how analyses are set up in the different programs. Subsequently, the software is assessed with respect to the following criteria: requirements, methodological options, and ease-of-use. Next, estimation results for different simulated data sets, each focusing on a specific issue, are compared. Finally, the main conclusions of the study are discussed.

2 PLS Path Modeling Software

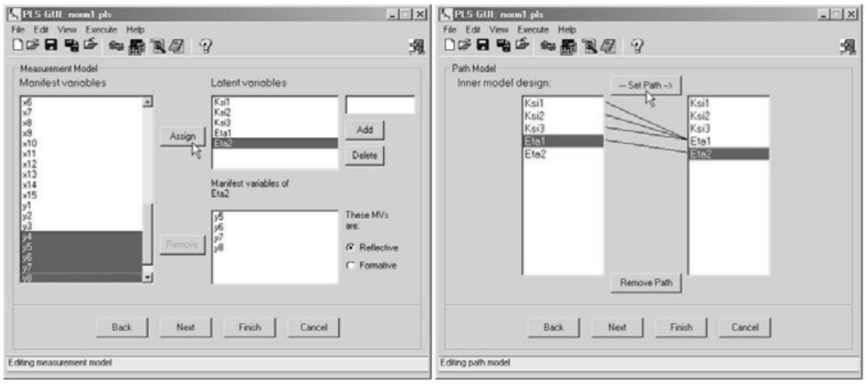
Besides *LVPLS*, the software overview includes several more recent software packages for PLS path modeling: *PLS-GUI*, *VisualPLS*, *PLS-Graph*, *SPAD-PLS*, and *SmartPLS*. Following the description of *LVPLS*, we will discuss *PLS-GUI* and *VisualPLS* which are basically graphical interfaces to *LVPLS*. Finally, the remaining programs are characterized. In contrast to the former software, these programs are more or less self-contained implementations of the algorithms developed by Wold (1982, 1985) and Lohmöller (1987). This review includes those program versions available to the authors as of August 2006. It should be noted, that all programs (except *LVPLS*) are constantly under development and can therefore be expected to offer additional features in the future.

LVPLS: The DOS-based program *LVPLS 1.8* (Lohmöller, 1987) includes two different modules for estimating path models. Whereas LVPLSC analyzes the covariance matrix of the observed variables, the LVPLSX module is able to process raw data. In order to specify the input file an external editor is necessary. The input specification requires that the program parameters are defined at specific positions in the file – a format which resembles punchcards (see upper panel in Figure 1). Results are reported in a plain text file. The program offers blindfolding and jackknifing as resampling methods in case raw data has been analyzed. When analyzing covariance/correlation matrices, resampling techniques cannot be applied.

PLS-GUI: The Windows-based *PLS-GUI* (Li, 2005) provides a graphical interface for *LVPLS* which supports both the analysis of raw data (LVPLSX) as well as covariance information (LVPLSC). To specify a model,



LVPLS



PLS-GUI

Fig. 1. Specification of Path Models in PLS Software: *LVPLS*, *PLS-GUI*

the user is led through a stepwise procedure which offers a menu at each step (see lower panel in Figure 1). Additional options (e.g., weighting schemes, missing data code) are to be chosen in a separate window. The program finally creates an input file which is processed by the executable file pls.exe of *LVPLS*. If required, the input file can be modified by the user. The output is the same as for *LVPLS*. The current version offers a bootstrap option as an additional feature not provided by *LVPLS*.

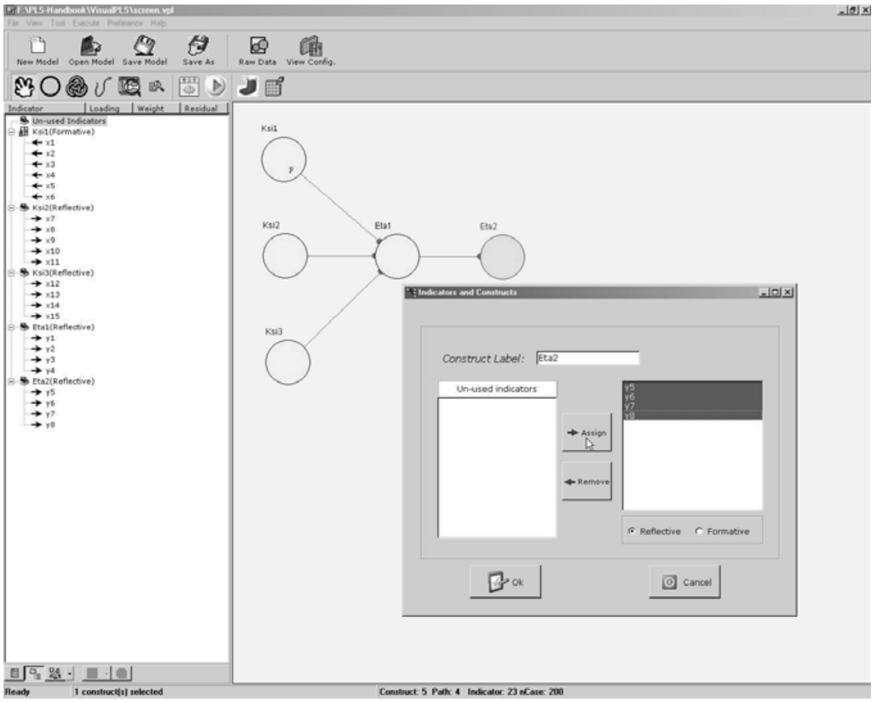
VisualPLS: *VisualPLS* (Fu, 2006a) is a graphical user interface for *LVPLS* running in the Windows environment which enables the analysis of raw data only. The path model is specified by drawing the latent variables and by assigning the indicators in a pop-up window (see upper panel in Figure 2). Based on the graphical model, the program produces a separate

LVPLS input file, which is run by LVPLSX (pls.exe). Different formats of input data are supported. The results are offered as *LVPLS* output (plain text file) as well as in HTML/Excel format. In addition, a path model showing the estimated parameters is displayed. Beyond blindfolding and jacknifing, bootstrapping has been integrated. Special support for specifying moderating effects and second order factors is offered.

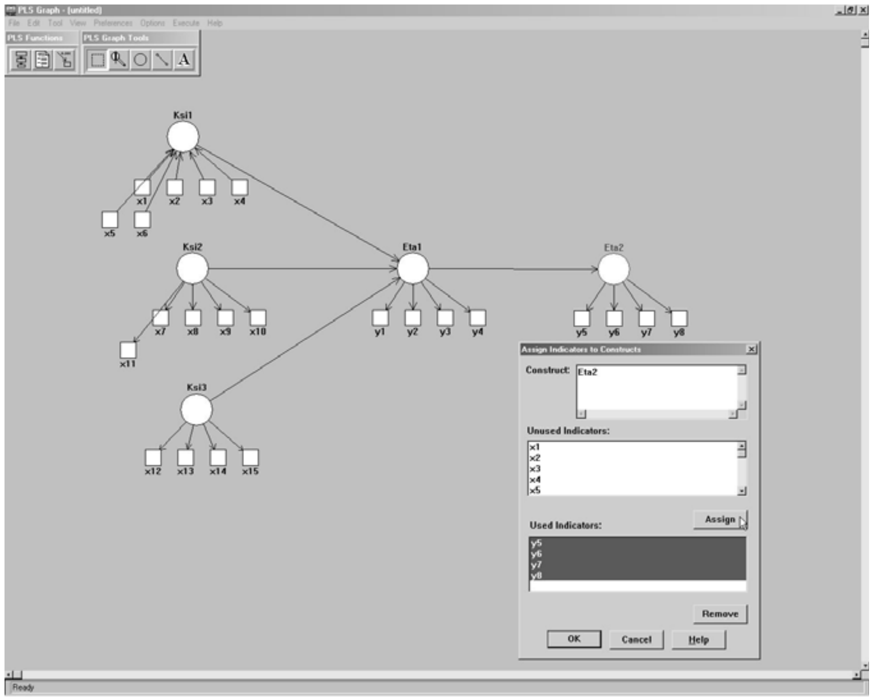
PLS-Graph: *PLS-Graph* (Chin, 2003) is a Windows-based program which uses modified routines of *LVPLS*, but only processes raw data (LVPLSX). In order to specify the model, a graphical interface can be used which provides some tools for drawing a path diagram (see lower panel in Figure 2). Different options (e. g., weighting scheme, resampling method) can be chosen from a menu. Although the generated input file is a text file, it can only be processed by *PLS-Graph*, but not by *LVPLS*. Estimation results are presented in ASCII format as well as in a graphical path model; resampling methods include blindfolding, jackknifing, and bootstrapping.

SPAD-PLS: This program is part of the comprehensive data analysis software SPAD (running under Windows) which is offered by the French company Test&Go. *SPAD-PLS* (Test&Go, 2006) does not process covariance information but needs raw data instead. Models can be specified with a menu or graphically in a Java applet; the remaining settings may be adjusted in additional menu windows (see upper panel in Figure 3). Different options for handling missing data (but see section 3.2) and multicollinearity are provided. Results are reported both as a path diagram and as text or Excel file; blindfolding, jackknifing, and bootstrapping (including confidence intervals) are available. In the non-graphical manual mode transformations of latent variables (squares, cross-products) can be specified.

SmartPLS: Since *SmartPLS* (Ringle et al., 2005) is Java-based, it is independent from the user's operating system. Again, only raw data can be analyzed. The model is specified by drawing the structural model for the latent variables and by assigning the indicators to the latent variables via "drag & drop" (see lower panel in Figure 3). The output is provided in HTML, Excel or Latex format, as well as a parameterized path model. Bootstrapping and blindfolding are the resampling methods available. Like in *VisualPLS*, the specification of interaction effects is supported. A special feature of *SmartPLS* is the finite mixture routine (FIMIX). Such an option might be of interest if unobserved heterogeneity is expected in the data (McLachlan and Peel, 2000).

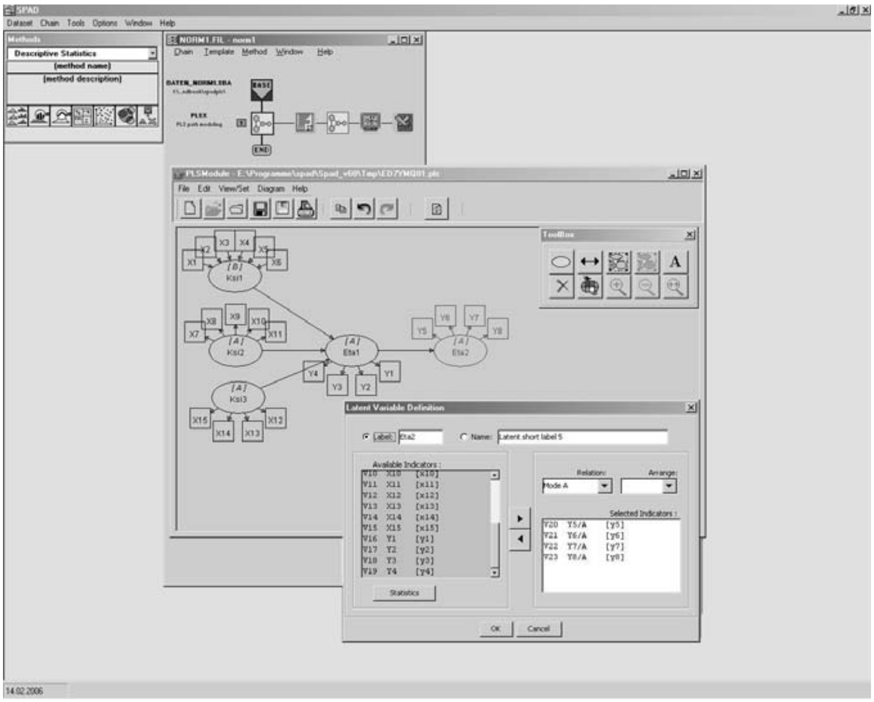


VisualPLS

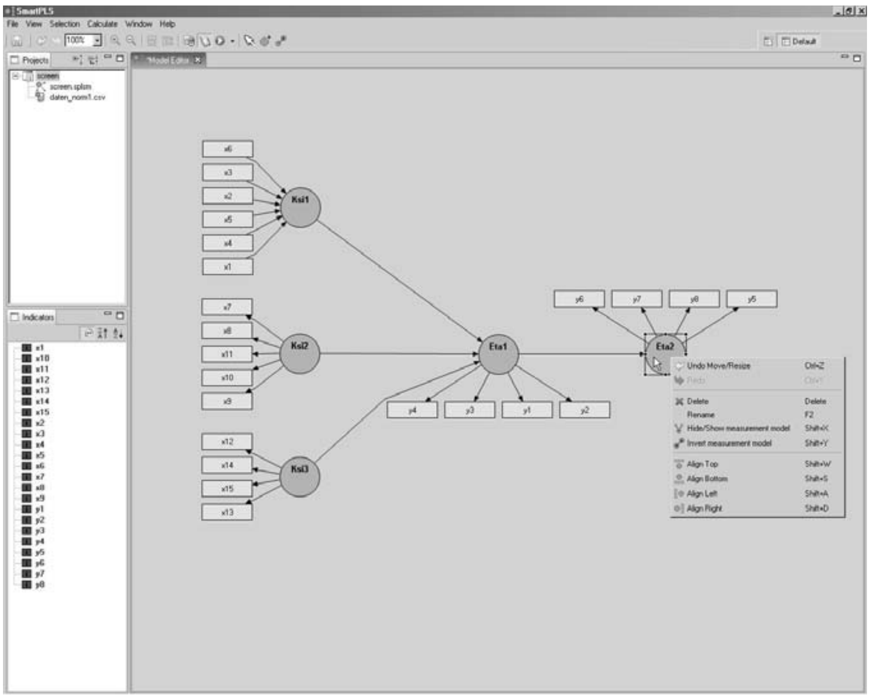


PLS-Graph

Fig. 2. Specification of Path Models in PLS Software: *VisualPLS*, *PLS-Graph*



SPAD-PLS



SmartPLS

Fig. 3. Specification of Path Models in PLS Software: *SPAD-PLS*, *SmartPLS*

3 Comparison and Recommendations

In order to support the user in making an informed decision about the software to be used in his/her study, programs are compared with respect to several features which can be subsumed under the following headings: requirements (e. g., operating system, data), methodological options (e. g., weighting scheme, resampling methods), and ease-of-use (e.g., specification, output format). In addition, we also point to some issues the researcher should pay attention to when using a specific program. The main properties of the programs are summarized in Tables 1, 2, and 3.

3.1 Requirements

Comparing the software with respect to their system requirements reveals that users of UNIX/LINUX or Mac systems have to use the platform-independent *SmartPLS* program. Further requirements concern the analyzed data. All programs at present expect that the indicators of the latent variables are continuous, or – for instance in the case of rating scales with 5 or more answer categories – approximate a continuous scale. In addition, binary exogenous variables can be included in the analysis. If only covariance matrices are available as data input, the choice is currently restricted to *LVPLS* or *PLS-GUI*. Except for *LVPLS*, all programs require a common definition of missing values for all variables (e.g., -999). In general, all programs are able to process ASCII data although some software requires a conversion into specific data formats (e.g., .sba in *SPAD-PLS*). *SPAD-PLS* also supports data formats of common software packages like SPSS and SAS which are converted in a data editor or exchange module.

3.2 Methodological Options

Missing Data

Data sets where at least some values of their variables are missing are ubiquitious in empirical research. In order to deal with missing data, several alternative approaches have been proposed (e. g., Little and Rubin (2002)). *LVPLS* offers a specific treatment in the case of missing data which combines mean value imputation and pairwise deletion in the course of the estimation (Lohmöller (1984); for a more comprehensive description see Tenenhaus et al. (2005)). This missing data treatment is also provided by the graphical interfaces (*PLS-GUI*, *VisualPLS*) as well as by *PLS-Graph* and *SPAD-PLS*. In contrast, *SmartPLS* offers two options equivalent to some data pre-processing which either substitute the mean over all available cases of a variable for the missing values or which delete those cases with missing data (casewise deletion). Since casewise deletion throws away a lot of useful information and thus leads to lower efficiency, this procedure is not to be recommended. Even the

<table>
<tr><th colspan="2">Features</th><th>LVPLS 1.8
Lohmöller (1987)</th><th>PLS-GUI 2.0.1
Li (2005)</th></tr>
<tr><td rowspan="5">Requirements</td><td>Operating system</td><td>DOS</td><td>Windows</td></tr>
<tr><td>Data</td><td colspan="2">Raw data / covariance matrix</td></tr>
<tr><td>Scale level</td><td colspan="2">Metric / binary exogenous variables</td></tr>
<tr><td>Definition of missing values (MV)</td><td>Individual definition of MV for each variable</td><td>Common definition of MV for all variables</td></tr>
<tr><td>Data format</td><td>.inp (ASCII)</td><td>.dat (ASCII)</td></tr>
<tr><td rowspan="5">Methodology</td><td>Data metric</td><td colspan="2">• Mean=0, Var=1
• Mean=0, Var=1, rescal.
• Mean=1, rescal.
• Original</td></tr>
<tr><td>Missing data treatment</td><td colspan="2">Fixed (pairwise elimination and/or imputation of means (see Section 3.2))</td></tr>
<tr><td>Weighting scheme</td><td colspan="2">Factor-, centroid-, or path weighting</td></tr>
<tr><td>Resampling</td><td>• Blindfolding
• Jackknifing</td><td>• Blindfolding
• Jackknifing
• Bootstrapping</td></tr>
<tr><td>Cross-validation</td><td>• CV-redundancy
• CV-communality</td><td>Not available</td></tr>
<tr><td rowspan="6">Ease-of-use</td><td>Specification</td><td>Text editor</td><td>Quasi graphically</td></tr>
<tr><td>Output</td><td colspan="2">ASCII</td></tr>
<tr><td>Graphical output</td><td colspan="2">Not available</td></tr>
<tr><td>Documentation</td><td>Lohmöller (1984)</td><td>Li (2003)</td></tr>
<tr><td>Internet</td><td>not available</td><td><code>http://dmsweb.moore.sc.edu/yuanli/pls-gui/</code></td></tr>
<tr><td>Availability</td><td colspan="2">Freeware</td></tr>
</table>

Table 1. Overview of PLS Path Modeling Software (Part 1)
Details represent the stage of development as of August 2006.

other traditional methods of dealing with missing data (i.e., pairwise deletion, mean imputation) have several shortcomings such as computing covariances (mode B) based on different sample sizes and biased parameter estimates (Allison (2002), Haitovsky (1968)), for example. Meanwhile, more advanced data imputation methods are announced for the next release of *SPAD-PLS* which will include an EM algorithm as well as the NIPALS approach.

Multi-collinearity

Multi-collinearity can be a problem both for the estimation of indicator weights in the case of formative constructs (mode B) and for the estimation

<table>
<tr><th colspan="2">Features</th><th>VisualPLS 1.04
Fu (2006a)</th><th>PLS-Graph 3.00
Chin (2003)</th></tr>
<tr><td rowspan="5">Requirements</td><td>Operating system</td><td colspan="2">Windows</td></tr>
<tr><td>Data</td><td colspan="2">Raw data</td></tr>
<tr><td>Scale level</td><td colspan="2">Metric / binary exogenous variables</td></tr>
<tr><td>Definition of missing values (MV)</td><td colspan="2">Common definition of MV for each variable</td></tr>
<tr><td>Data format</td><td>.dat (ASCII), .csv</td><td>.raw (ASCII)</td></tr>
<tr><td rowspan="7">Methodology</td><td>Data metric</td><td colspan="2">• Mean=0, Var=1
• Mean=0, Var=1, rescal.
• Mean=1, rescal.
• Original</td></tr>
<tr><td>Missing data treatment</td><td colspan="2">Fixed (pairwise elimination and/or imputation of means (see Section 3.2))</td></tr>
<tr><td>Weighting scheme</td><td colspan="2">Factor-, centroid-, or path weighting</td></tr>
<tr><td>Resampling</td><td colspan="2">Blindfolding, jacknifing, and bootstrapping</td></tr>
<tr><td>Cross-validation</td><td colspan="2">CV-redundancy and CV-communality</td></tr>
<tr><td>Special features</td><td>Interaction- and 2nd-order factor model support</td><td>Individual and construct level sign correction for bootstrapping</td></tr>
<tr><td rowspan="6">Ease-of-use</td><td>Specification</td><td colspan="2">Graphically</td></tr>
<tr><td>Output</td><td>ASCII, Excel, HTML</td><td>ASCII</td></tr>
<tr><td>Graphical output</td><td colspan="2">Path diagram</td></tr>
<tr><td>Documentation</td><td>Fu (2006b)</td><td>Chin (2001)</td></tr>
<tr><td>Internet</td><td><code>http://www2.kuas.edu.tw/prof/fred/vpls/index.html</code></td><td><code>http://www.cba.uh.edu/plsgraph/</code></td></tr>
<tr><td>Availability</td><td colspan="2">Freeware</td></tr>
</table>

Table 2. Overview of PLS Path Modeling Software (Part 2)
Details represent the stage of development as of August 2006.

of the relationships among latent variables. Possible means to detect severe multi-collinearity with respect to formative indicators are inspecting the correlation matrix, calculating the variance inflation factors, or examining the condition index. *SPAD-PLS* at present is the only program which addresses the problem of multi-collinearity by providing a PLS regression routine for estimating weights (Mode PLS) and path coefficients (PLS regression instead of OLS regression). PLS regression searches for a set of components which decompose the vector y of the endogenous variable and the matrix X of explanatory variables in such a way that the explained covariance between y and X is maximized.

	Features	*SPAD-PLS* Test&Go (2006)	*SmartPLS 2.0 M3* Ringle et al. (2005)
Requirements	Operating system	Windows	Independent (Java)
	Data	Raw data	
	Scale level	Metric / binary exogenous variables	
	Definition of missing values (MV)	Common definition of MV for each variable	
	Data format	.sba (ASCII, SPSS, SAS)	.txt (ASCII), .csv
Methodology	Data metric	• Mean=0, Var=1 • Mean=0, Var=1, rescal. • Mean=1, rescal. • Original	
	Missing data treatment	Pairwise elimination or imputation of means, NIPALS/EM*	Casewise elimination or imputation of means
	Weighting scheme	Factor-, centroid-, or path weighting	
	Resampling	• Blindfolding • Jackknifing • Bootstrapping	• Blindfolding • Bootstrapping
	Cross-validation	• CV-redundancy • CV-communality	• CV-redundancy • CV-communality
	Special features	PLS regression for weights and path coefficients; confidence intervals for jackknifing and bootstrapping; contribution to R^2; check of unidimensionality of latent variables (eigenvalues)	Finite-mixture PLS; Interaction model support; Cronbach's alpha
Ease-of-use	Specification	Graphically	
	Output	ASCII, Excel	HTML, Latex, Excel
	Graphical output	Path diagram	
	Documentation	Vinzi et al. (2004)	Hansmann and Ringle (2004)
	Internet	`http://www.testandgo.com`	`http://www.smartpls.de`
	Availability	Test&Go	Freeware

* not implemented in the test version used for this review

Table 3. Overview of PLS Path Modeling Software (Part 3)
Details represent the stage of development as of August 2006.

Resampling Methods

Since one of the appealing features of PLS path modeling is the fact that it does not rest on any distributional assumptions, significance levels for the parameter estimates which are based on normal theory are, strictly speaking, not suitable. Therefore, information about the variability of the parameter estimates and hence their significance has to be generated by means of resampling procedures. Whereas *LVPS* only offers blindfolding and jacknifing, all recent software packages include a bootstrap option. In order to assess the quality of the estimated model, several criteria for model validation have been proposed in the literature (for a discussion see, for example, Tenenhaus et al. (2005)). To calculate cross-validation indices, blindfolding is necessary and now offered by all programs. Except for *PLS-GUI*, cross-validated communality and redundancy measures are also provided in the programs' output by request.

In order to derive valid standard errors or t-values, applying bootstrapping is superior to the other two resampling methods. Therefore, in the following we will focus on the former. The bootstrap procedure approximates the sampling distribution of an estimator by resampling with replacement from the original sample. An important issue is that in PLS the signs of the latent variables are indetermined. Since arbitrary sign changes in the parameter estimates of the various bootstrap samples can increase their standard error to a substantial degree, procedures have been developed to correct for sign reversals. Here, both *PLS-Graph* and *SmartPLS* allow the user to choose between two correction procedures: In the first option (individual sign changes), the sign of each individual outer weight is made equal to the corresponding sign in the original sample. Because this procedure does not check for the overall coherence of the model as would be done if mental "reverse coding" (Chin, 2000) were performed, this option should be used with special care. The second option (construct level changes) compares the loadings for each latent variable with the original loadings and reverses the sign of the weights if the absolute value of the summed difference between the original and the bootstrap loadings is greater than the absolute value of the sum of the original loadings and the bootstrap loadings (Tenenhaus et al., 2005). However, both procedures do not guarantee that sign changes are properly handled. The graphical interfaces *PLS-GUI* and *VisualPLS* only offer construct level correction. Since *SPAD-PLS* uses the elements of the first eigenvector of a principal components analysis with predominantly positive signs, sign control aligns the signs in the bootstrap samples to those of the original sample.

Another possibility to gauge the significance of the PLS estimates is to calculate the confidence intervals from the bootstrap samples. So far this option using the percentile method is only implemented in *SPAD-PLS*.

Other Features

With respect to the inner weights, all programs offer the weighting schemes for estimating the inner model (centroid-, factor-, and path weighting) already available in *LVPLS*. A topic of special interest is the use of different sets of starting values for determining the outer weights. The starting values can have an impact on the sign of the estimated weights or factor loadings and therefore also on the path coefficients (see the simulation results for data set 1 in Section 4). Although this is not a statistical issue, it is important for the interpretation of the estimation results. None of the programs currently allow users to specify their own set of starting values. For those programs with fixed starting values (*LVPLS*, *PLS-GUI*, *VisualPLS*, *PLS-Graph*, and *SmartPLS*), rearranging the order of indicators in a single block is the only means of exerting an influence on the sign (Tenenhaus et al., 2005). In *SPAD-PLS*, starting values are flexible insofar as the elements of the first eigenvector of a principal components analysis (PCA) with predominantly positive signs are used (Tenenhaus et al., 2005). *SPAD-PLS* provides normalized weights if all outer weights are positive as well as latent variable scores in the original metric.

3.3 Ease-of-Use

Compared to *LVPLS*, all recent PLS software is considerably more user-friendly. This is especially true for programs where the user can specify the model graphically and where the program displays a parameterized path diagram as output (*VisualPLS*, *PLS-Graph*, *SPAD-PLS*, and *SmartPLS*). Particularly mentionable are the following features: In *PLS-Graph*, *SPAD-PLS*, and *SmartPLS*, it is easy to change the data set without having to specify the model again. Additionally, it is possible to save the complete analysis (including data set, model, and results) into a single project file.

VisualPLS and *SmartPLS* both give assistance in constructing product indicators for path models with interaction effects. The user can choose between mean centering and standardizing the corresponding manifest variables. Whereas *VisualPLS* only calculates product terms and includes them as new variables, *SmartPLS* directly adds the latent interaction term with its measures to the graphical path model. The program even modifies the indicator product terms automatically if the measurement models of the latent predictor/moderator variables are changed. In the case of reflective indicators, the interaction module is a convenient feature. However, the option should not be used in the case of formative constructs (for a discussion of estimating interaction effects in PLS path modeling see Chin et al. (2003)).

Most programs provide rich tool boxes which help to improve the layout of the path diagrams (color, size, text etc.). This especially applies to *SPAD-PLS* and *SmartPLS*. Even though graphical tools are not available under *PLS-GUI*, model specification is nevertheless fairly easy. For all programs, user manuals document the application with example data. Additional information on *SPAD-PLS*, but also on PLS path modeling in general, can be accessed on the website `www.esisproject.com` of the European Satisfaction Index System (ESIS). Overall, PLS path analyses can be performed after a few initial practice sessions with all of the recent software.

4 Comparison Based on Simulated Data

Since all programs for PLS path modeling more or less use the same basic algorithms, estimation results should not differ for data sets without any "problematic" characteristics. In order to provoke distinct results, we therefore created three different data sets, each focusing on a specific issue: First, we demonstrate that programs can produce different solutions with respect to the parameter signs under certain conditions. Second, parameter estimates differ across programs if missing data are present. Third, we focus on the case that latent exogenous variables show a substantial degree of multi-collinearity. Since the programs' capabilities to cope with the data characteristics described above in part differ, the three simulated data sets have been analyzed with *PLS-GUI*, *VisualPLS*, *PLS-Graph*, *SPAD-PLS*, and *SmartPLS*. All data simulations have been performed in the statistical environment R.

4.1 Data Set 1 – Sign Changes and Bootstrapping

The first data set ($N = 200$) has been generated according to the parameterized path model in Figure 4. Because specification issues with respect to the measurement models for latent variables (reflective versus formative models) have recently been discussed rather intensively in the marketing research literature (e. g., Diamantopoulos and Winklhofer (2001), Jarvis et al. (2003)), we specify two different kinds of measurement models for the exogenous latent variables (ξ_1: formative/mode B, ξ_2 and ξ_3: reflective/mode A). Since formative indicators do not necessarily imply a specific pattern of correlations among them (Nunnally and Bernstein, 1994), a negative influence of the manifest variables x_5 and x_6 on the latent variable ξ_1 has been specified. For both endogenous variables η_1 and η_2, only reflective measurement models are supposed (mode A).

Comparing the results for the programs used in our study reveals the following: Absolute parameter values are almost identical across the programs. For specific relations, however, the signs differ across the software packages (as reported in Table 4). Whereas *PLS-GUI*, *VisualPLS* and *SPAD-PLS* reproduce the signs of the population values used for the simulation, *PLSGraph* and *SmartPLS* generate opposite signs for the weights of the indicators x_1 to x_6. As a consequence, the estimated effect of the exogenous latent variable ξ_1 on the latent endogenous variable η_1 differs likewise. This finding can be

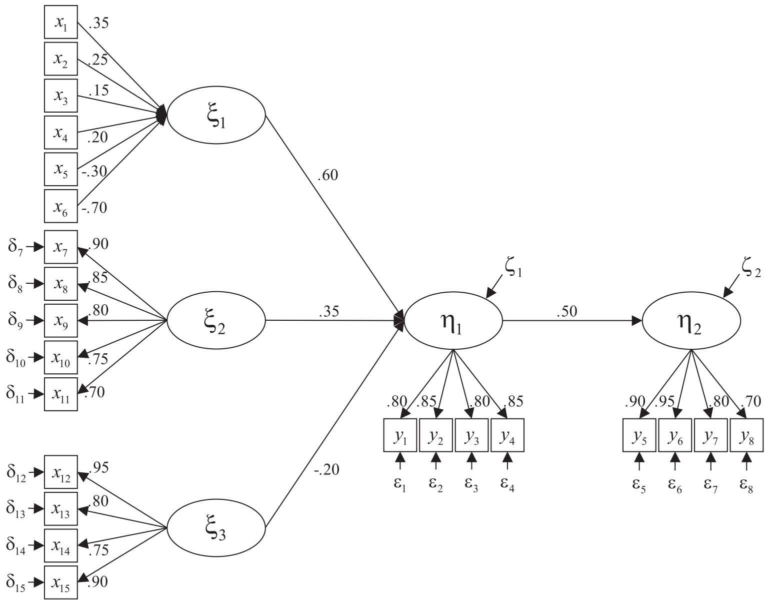


Fig. 4. Path Model Used for Simulating Data Set 1 (all variables are standardized)

explained by different sets of starting values. Whereas *LVPLS* uses the sequence $1, 1, \ldots, -1$ as starting values for each block, *SmartPLS*, for example, uses the value 1 for all weights of a block. By performing mental "reverse coding" (Chin, 2000), the different solutions can be aligned. Thus, from a statistical point of view, sign changes across the programs are not an issue, but applied researchers should be sensitized to think thoroughly about the expected signs of the relationships between the manifest and latent variables as well as the effects between the latent variables. A peculiar finding emerges for *VisualPLS*: The signs for the weights of the formative construct ξ_1 and the path coefficient for its effect on η_1 in *LVPLS* (see Table 4) are reversed in the displayed path model. Since the reversed signs are used in the bootstrap procedure, they are reported in Table 5.

As discussed above, arbitrary sign changes can have a severe influence on the bootstrap results if not properly controlled for. Therefore, 500 bootstrap samples (each with $N = 200$) have been analyzed with the various programs. Construct level sign change is applied since for ξ_1 the signs of the weights differ within the block. The results with respect to the bootstrap means/standard errors and the t-ratios are reported in Table 5. There are substantial differences

			Programs		
			All	*PLS-GUI/ VisualPLS/ SPAD-PLS*	*PLS-Graph/ SmartPLS*
			Absolute values	*Signs*	
Measurement model ξ_1	*Weights*	x_1	0.073	+	-
		x_2	0.339	+	-
		x_3	0.225	+	-
		x_4	0.335	+	-
		x_5	-0.345	-	+
		x_6	-0.822	-	+
Structural model	*Path coeff.*	$\xi_1 \to \eta_1$	0.447	+	-
		$\xi_2 \to \eta_1$	0.323	+	+
		$\xi_3 \to \eta_1$	-0.180	-	-
		$\eta_1 \to \eta_2$	0.482	+	+

Table 4. Comparisons of the Results for Data Set 1 – Estimates and Signs for Selected Parameters

in the time needed for the different programs to produce the bootstrap results for our sample. *SPAD-PLS* is by far the fastest software (the run took less than 5 seconds), followed by *SmartPLS* and *PLSGraph* (about 30 seconds). Both graphical interfaces for *LVPLS*, i. e. *PLS-GUI* and *VisualPLS* were rather slow in providing the bootstrap estimates (about 1 minute and 40 seconds).

Whereas the graphical interfaces for *LVPLS* as well as *PLS-Graph* and *SmartPLS* produce similar results, both the bootstrap means/standard errors and the t-ratios of *SPAD-PLS* in part differ considerably. For example, for the path of ξ_1 to η_1 the t-ratio is less than half the ratio which results from the other programs; the same applies to the weight for x_6. These differences might be explained by the idiosyncratic way *SPAD-PLS* determines the starting values for each block and the corresponding sign control (Tenenhaus et al., 2005, p. 184). However, *SPAD-PLS* does not consistently produce the lowest t-ratios.

4.2 Data Set 2 – Missing Data

In order to compare the results of the different programs in the case of missing data, a very simple model is used for data simulation in which a formative construct only influences one latent variable measured by reflective indicators.

			Original estimate	Bootstrap														
				means					*standard errors*					*t-ratios*				
				PLS-GUI	*Visual PLS*	*PLS-Graph*	*SPAD-PLS*	*Smart PLS*	*PLS-GUI*	*Visual PLS*	*PLS-Graph*	*SPAD-PLS*	*Smart PLS*	*PLS-GUI*	*Visual PLS*	*PLS-Graph*	*SPAD-PLS*	*Smart PLS*
Measurement model ξ_1	*Weights*	x_1	0.073	0.070	-0.127	-0.056	0.078	-0.073	0.139	0.092	0.144	0.139	0.138	0.525	-0.790	-0.511	0.527	-0.528
		x_2	0.339	0.325	-0.321	-0.336	0.371	-0.318	0.114	0.123	0.113	0.150	0.119	2.974	-2.763	-3.011	2.260	-2.843
		x_3	0.225	0.225	-0.222	-0.239	0.242	-0.219	0.125	0.110	0.116	0.135	0.120	1.800	-2.047	-1.941	1.679	-1.887
		x_4	0.335	0.314	-0.321	-0.305	0.358	-0.303	0.125	0.121	0.139	0.132	0.132	2.680	-2.761	-2.426	2.536	-2.544
		x_5	-0.345	-0.334	0.317	0.314	-0.366	0.333	0.137	0.134	0.131	0.152	0.138	-2.518	2.577	2.638	-2.271	2.501
		x_6	-0.822	-0.784	0.794	0.785	-0.881	0.790	0.091	0.086	0.090	0.203	0.092	-9.033	9.575	9.182	-4.048	8.921
Structural model	*Path coeff.*	$\xi_1 \rightarrow \eta_1$	0.447	0.459	-0.460	-0.459	0.457	-0.460	0.049	0.050	0.048	0.108	0.052	9.122	-8.932	-9.228	4.130	8.666
		$\xi_2 \rightarrow \eta_1$	0.323	0.321	0.318	0.322	0.323	0.326	0.051	0.055	0.052	0.045	0.054	6.333	5.870	6.169	7.205	5.950
		$\xi_3 \rightarrow \eta_1$	-0.180	-0.184	-0.182	-0.190	-0.191	-0.181	0.053	0.048	0.056	0.069	0.052	-3.396	-3.779	-3.217	-2.617	3.447
		$\eta_1 \rightarrow \eta_2$	0.482	0.485	0.482	0.482	0.476	0.486	0.051	0.053	0.053	0.040	0.054	9.451	9.042	9.135	12.103	8.897

Table 5. Comparisons of the Bootstrap Results for Data Set 1 – Selected Parameters

Since in *LVPLS* missing data treatment depends on whether data is missing on a whole block or just on some (but not all) manifest variables, two different missing data schemes are applied. For the formative construct it is assumed that values are missing for only some manifest variables. In contrast, for the reflective endogenous latent variable, missing data are produced such that values are absent for all of its indicators. Missing data (about 10 % for each variable) have been generated completely at random (MCAR).

Since the programs in part offer different options in the case of missing data, some discrepancies in the results are expected. However, at least the graphical interfaces for *LVPLS* (*PLS-GUI*, *VisualPLS*) should produce the same results as Lohmöller's program. The actual results nevertheless show unexpected differences. Obviously, these differences are caused by an incorrect setup of the input file to *LVPLS*. In both interfaces one is allowed to specify one specific value for missing data (e.g., -1) which is then used to add a "missing data case" to the data. In the input file, this value should exactly correspond to the missing data values in the raw data. In *PLS-GUI* and *VisualPLS*, however, this code is transferred in a way which does not correspond to the Fortran format specified for reading the data. If the raw data has decimal places, this means that the missing data code differs from the missing values contained in the data. For example, in the following input file generated by *PLS-GUI* the variables have four decimal places. For the given Fortran format, a value of -1 (for missing data) is written as -10000 whereas the missing data case includes a -1 instead.

```
COMMENT
LVPLS input file generated by PLS-GUI 2.0.1
CEND
PLSX
Missing Data - Demonstration
   2-201   12255   2 100   0   1   0   0
   6   4
   1   0
   1   1
      x1      x2      x3      x4      x5      x6      y1      y2      y3
      y4
 0 011  (2A4,2F2.0)
     Ksi . .
     Eta 1 .
 0 0 0 0(2A4,10F8.4)
MISSING       -1      -1      -1 ...      -1      -1      -1      -1
Case   1   -1376  -10000    4377 ...   -3641    4779   -4490   -4477
Case   2   -3732  -12294  -10674 ...   -8361   13691   -5158   -1034
Case   3    6682   12600   -3648 ...   -2730   -9584   -2378   -3407
Case   4    3872  -11195   13664 ...   -1358   10213   -5583    8641
Case   5    7190  -15879  -10000 ...  -10000  -10000  -10000  -10000
Case   6  -17634  -10000   19101 ...  -15699   -8155   -3705  -14140
...
Case 199    4730  -17174    8129 ...   10000   19261   12698    9710
Case 200  -14363  -10805   -1490 ...   -3009    2840    4169    2750
STOP
```

Correcting the wrong coding in the missing data case of the input file for *LVPLS* produced by the interfaces and running it with the executable PLS file leads to the correct results. In *PLS-Graph* and *SPAD-PLS*, the missing data procedure is implemented correctly. The more advanced methods to deal with missing data (EM algorithm, NIPALS) announced for *SPAD-PLS* were not available in the test version for this review. Since *SmartPLS* only allows for mean imputation or casewise deletion, different results emerge compared to the other programs.

4.3 Data Set 3 – Multi-collinearity

Multi-collinearity can be a problem for the estimation of the relationships within (formative) measurement models as well as the effects among the latent variables. So far *SPAD-PLS* is the only program which takes this problem into account by offering an option to use PLS regression in the estimation of the outer weights and the path coefficients. Here we only focus on the problem of multicollinearity at the latent construct level. We therefore compare the results of *SPAD-PLS* with PLS regression in the case of multi-collinearity with the results of the remaining programs based on common OLS regressions. A data set ($N = 100$) with five correlated exogenous latent variables has been created (see the model in Figure 5).

The resulting variance inflation factors (VIF) for these constructs are between VIF = 16 and VIF = 38. According to general rules of thumb (e.g., Kutner et al. (2004)), values above VIF = 10 allude to a potentially severe problem of multi-collinearity. The results reported in Table 6 show very similar estimates for the path coefficients both under OLS and PLS regression. In addition, the highest contribution to R^2 is determined for those two exogenous variables which have the smallest "true" effect size (ξ_2 and ξ_4). Given the great discrepancies between the "true" values and the estimated coefficients, *SPAD-PLS* does not really seem to cure the problem of multi-collinearity, at least in our data set.

			True values	*OLS regression*	*PLS regression*
Structural model	*Path coefficients*	$\xi_1 \to \eta_1$	0.50	-0.003	0.029
		$\xi_2 \to \eta_1$	-0.15	0.382	0.378
		$\xi_3 \to \eta_1$	0.25	0.156	0.114
		$\xi_4 \to \eta_1$	0.10	0.288	0.298
		$\xi_5 \to \eta_1$	0.30	0.004	0.008
		$\eta_1 \to \eta_2$	0.40	0.441	0.441

Table 6. Comparisons of the Results for Data Set 3 – OLS versus PLS Regression Path Coefficients

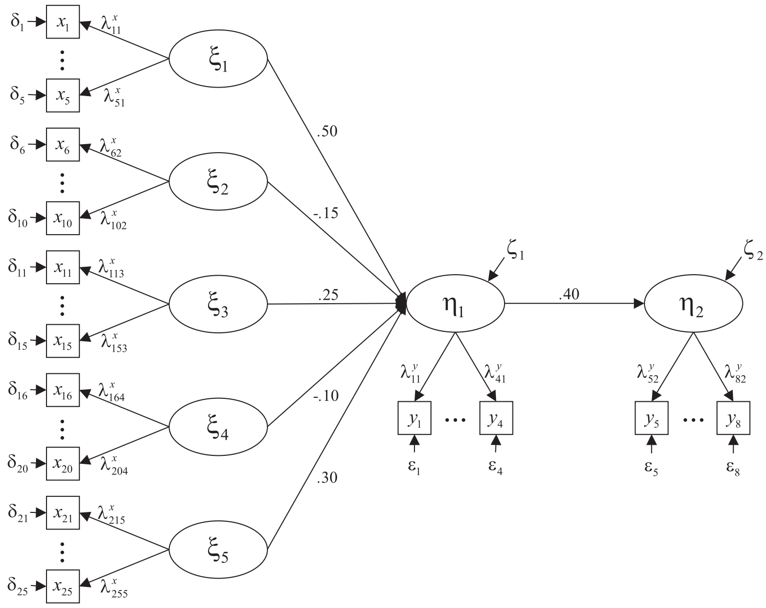


Fig. 5. Path Model Used for Simulating Data Set 3 (all variables are standardized)

5 Conclusion

In this review on PLS path modeling programs, *LVPLS* and the more recent software packages (*PLS-GUI*, *VisualPLS*, *PLSGraph*, *SPAD-PLS*, and *SmartPLS*) have been characterized and compared with each other. A special emphasis has been placed on the criteria ease-of-use and methodological options. Whereas specifying path models in *LVPLS* is rather inconvenient, all recent programs have made a huge step with respect to ease-of-use, reaching now the same level as the software used in covariance structure analysis. Individual strengths in user-friendliness have been identified, such as supporting the estimation of interaction effects (*VisualPLS* and *SmartPLS*) and helpful export options (*SPAD-PLS* and *SmartPLS*).

One main methodological improvement is the bootstrap procedure for assessing the significance of parameter estimates, which is now implemented in all software packages and supplements the blindfolding and jacknifing resampling routines of *LVPLS*. A specific strength of *SPAD-PLS* is the estimation of bootstrap confidence intervals for the parameters. Model validation is another important aspect; although some measures like the goodness-of-fit index

(Tenenhaus et al., 2005) have been discussed in the literature, so far only the blindfolding cross-validation indices (cv-redundancy and cv-communality) are offered. The performance of the different programs has also been tested on data sets with missing data and multi-collinearity. Here, both *PLS-GUI* and *Visual-PLS* provide an incorrect missing data code for the *LVPLS* input file. A major improvement in dealing with missing data is expected for the next release of *SPAD-PLS*.

Multi-collinearity is a problem both for the estimation of weights in the case of formative constructs and the estimation path coefficients. To cure this problem, *SPAD-PLS* has implemented a PLS regression routine. In our study, results for simulated data, however, are very similar to those resulting from OLS regression. This issue should be the subject of a comprehensive Monte Carlo study.

Overall, there is considerable demand for implementations of the various methodological advances documented, for example, in this volume.

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SFB 649, Spandauer Straße 1, D-10178 Berlin
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