Fit for a Bayesian: An evaluation of PPP and DIC for structural equation modeling

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2018

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This study was partially supported by a grant from the Department of Education (R305D140037). However, the contents of the study do not necessarily represent the policy of the Department of Education, and you should not assume endorsement by the Federal Government.
Citation: Cain, M., & Zhang, Z. (2018). Fit for a Bayesian: An evaluation of PPP and DIC for structural equation modeling.Structural Equation Modeling.

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Despite its importance to structural equation modeling, model evaluation remains underdeveloped in the Bayesian SEM framework. Posterior predictive p-values (PPP) and deviance information criteria (DIC) are now available in popular software for Bayesian model evaluation, but they remain under-utilized. This is largely due to the lack of recommendations and guidelines for their use. To address this problem, PPP and DIC are evaluated in a series of Monte Carlo simulation studies. The results from these studies show that PPP and DIC are influenced by severity of model misspecification, sample size, model size, and choice of prior. It was also found that the cut-offs PPP$<$0.10 and ΔDIC>7 work best in the conditions and models tested here to maintain false detection rates and misspecified model selection rates, respectively, at 0.05. The recommendations provided in this study will help researchers evaluate their models in a Bayesian SEM analysis, and set the stage for future development and evaluation of PPP, DIC, and other Bayesian SEM fit indices.

Keywords: Bayesian, posterior predictive p-values, deviance information criteria, structural equation modeling, model fit

The Bayesian framework offers a flexible approach to structural equation modeling (SEM; Kaplan & Depaoli, 2012; Lee, 2007; Palomo, Dunson, & Bollen, 2007; Raftery, 1993). Incorporation of prior knowledge allows estimation of under-identified models, a natural means of constraining parameters, and better small-sample performance (Scheines, Hoijtink, & Boomsma, 1999). Prior information is combined with the current sample through Bayes' Theorem, often using Markov chain Monte Carlo (MCMC) sampling and data augmentation. Although MCMC tends to be more computationally demanding for simple models, highly complex problems can be less computationally demanding through MCMC than through traditional methods (Berger, 2006). Data augmentation naturally handles issues such as missingness, nonlinearity, multilevel structure, and others (Lee, 2007). Lastly, because Bayesian SEM provides full posterior distributions for each parameter and latent variable, more can be learned about the model as a whole.

Bayesian SEM has many applications within the social sciences (Rupp, Dey, & Zumbo, 2004), but its utility continues to be limited in practical analysis largely due to the lack of guidelines and recommendations for model evaluation. Jordan (2011) has cited the lack of "off-the-shelf" methods for model selection the number one open problem in Bayesian statistics. Within the linear modeling framework, Bayes factor > 3 is a common criterion and has been found to correspond highly with the traditional $\alpha < 0.01$ criterion (Jeon & De Boeck, 2017). Within the SEM framework, however, a systematic evaluation of Bayesian model evaluation has yet to be conducted. This is particularly challenging because the traditional fit indices, such as T_{ML} , RMSEA (Steiger & Lind, 1980), or CFI (Bentler, 1990), are not available or well defined when performing Bayesian SEM.

Posterior predictive p-value (PPP; Gelman, Meng, & Stern, 1996; Meng, 1994) and deviance information criterion (DIC; Spiegelhalter, Best, Carlin, & Linde, 2014; Spiegelhalter, Best, Carlin, & Van Der Linde, 2002) are Bayesian methods of model evaluation available in popular software. Currently, DIC is the only measure of model fit available in WinBUGS (Lunn, Thomas, Best, & Spiegelhalter, 2000), and PPP and DIC are available in Mplus (L.K. Muthén & B.O. Muthén, 2012). Due to their availability, it is important for users to know what analysis features can affect PPP and DIC and how to interpret their values.

Posterior Predictive P-Value

PPP can be thought of as a Bayesian-motivated generalization of T_{ML}. It is a natural byproduct of the MCMC approximation, calculated using posterior predictive distributions of the same sample size and of the same likelihood as the original data. At each MCMC iteration j, a new set of data $\boldsymbol{Y}^j$ is generated based on updated parameter estimates, $\boldsymbol{\theta}^j$. A discrepancy statistic, such as T_{ML}, is calculated for each generated posterior predictive distribution, resulting in as many T_{ML} statistics as there are samples in the posterior. A T_{ML} statistic is also calculated for the sample data, $\boldsymbol{X}$, using each updated parameter estimate, $\boldsymbol{\theta}^j$. PPP is the proportion of posterior predictive discrepency statistics that are greater than the discrepency statistics of the current data,

$$\text{PPP} = p(T_{ML}(\boldsymbol{X}, \boldsymbol{\theta}^j) < \square_{ML}(\boldsymbol{Y}^j, \boldsymbol{\theta}^j)). \quad (1)$$

An excellent-fitting model is expected to have a PPP value around 0.5, and an extreme value indicates otherwise. In Mplus, a low PPP indicates that the model is not appropriate for this data and that there is misspecification (Asparouhov & Muthén, 2010b). Within the item response theory (IRT) framework, PPP can also be used for model comparison by comparing the number of items or item pairs with extreme PPP values across models (i.e. Zhu & Stone, 2012).

In practice, it is still largely unknown whether any cut-offs can be reliably used with PPP to detect misspecification. Cut-offs are useful because they can provide a dichotomous indicator of model fit: A PPP below a specified cut-off would indicate that the model does not fit the data, and a PPP above the cut-off would indicate that the model does fit the data. Because PPP is not uniformly distributed, it has no theoretical cut-off to maintain Type I error at 0.05 like p-values do (Hjort, Dahl, & Steinbakk, 2006). Cut-offs of 0.01, 0.05, and 0.10 have been proposed (Asparouhov & B.O. Muthén, 2010b; Gelman et al., 1996; B. O. Muthén & Asparouhov, 2012), but have not been thoroughly studied and compared.

Deviance Information Criterion

DIC is a generalization of AIC, in which the model complexity penalty is determined using the deviance of the hypothesized model (Spiegelhalter, Best, Carlin, & Van Der Linde, 2002). Operationally, at each MCMC iteration j the deviance is calculated using the updated parameter estimates, $\boldsymbol{\theta}^j$, and the current data, $\boldsymbol{X}$. The mean of these posterior deviances, $\overline{D}$, is compared to the deviance of the posterior mean, $D(\overline{\boldsymbol{\theta}})$, to obtain a calculation of model complexity,

$$p_D = \overline{D} - D(\overline{\boldsymbol{\theta}}). \tag{2}$$

DIC is then formulated the same way as AIC, with p_D replacing the number of parameters p:

$$DIC = -2\log\{p(\boldsymbol{X}|\boldsymbol{\theta})\} + 2p_D. \tag{3}$$

DIC was developed for models with hierarchical structure and in Bayesian analysis when using informative priors, because the effective number of parameters is no longer straightforward (Spiegelhalter et al., 2002). In linear models with noninformative priors, AIC and DIC are expected to be equal (Ellison, 2004). Like AIC, the target model of DIC is not the true model.

Rather, DIC tries to find the simplest model that fits the current data well (Plummer, 2006). Both AIC and DIC tend to prefer models that overfit the data in small samples (Ando, 2011; Plummer, 2008; van der Linde, 2005, 2012).

Although DIC has not been extensively tested through simulation, there are some reports of it working rather well. For example, Asparouhov, Muthén, and Morin (2015) found that DIC outperforms BIC in models with informative priors. Zhang, Lai, Lu, and Tong (2013) used DIC for model selection in a Bayesian growth curve model with good performance when the true model was the more complex model. In the same paper, however, DIC did not perform as well when the true model was the less complex model. DIC has been shown to prefer more complex testlet models within the IRT framework, as well (Li et al., 2006).

Like other information criteria, DIC does not follow a specified distribution, thus there is no formal test to compare two models. Cut-offs between 3 and 7 have been proposed to show sufficient evidence that the model with the smaller DIC fits better than the alternative model (Lee & Song, 2012; Spiegelhalter et al., 2002), but these have not been fully evaluated.

Simulation Studies

The objective of the current study is to evaluate the performance of PPP and DIC and to provide recommendations for their use. Specifically, it would benefit Bayesian SEM users to know which properties of the data or models influence PPP and DIC, so that they can appropriately interpret their values in a data analysis. Through two Monte Carlo simulation studies, this report will evaluate the impacts of model misspecification, sample size, model size, and choice of prior.

A model is said to be misspecified when one or more parameters are estimated whose population values are zero *(over-parameterization),* one or more parameters are fixed to zero

whose population values are nonzero *(under-parameterization)*, or both (Hu & Bentler, 1998). In addition to being sensitive to model misspecification, it is also desirable to have a fit index that is not sensitive to other features. There has been some previous research to show that PPP is sensitive to sample size (Asparouhov & Muthén, 2010a) and that DIC performance improves with sample size (Zhu & Stone, 2012), but little else is known about what other features of the data or model can affect PPP and DIC. Without this information, it is difficult to interpret PPP and DIC in a data analysis setting, especially if they contradict.

The first simulation study will evaluate the effects of sample size, model size, and model misspecification on PPP and DIC using different cut-off values. The second simulation study will evaluate the effect of prior choice. Using the results from both of these studies, the authors will provide recommendations and guidelines for the use of PPP and DIC in a practical Bayesian SEM analysis.

Simulation Design

Each simulation study uses one true model from which the data are generated. These data are then fit to the true model and five misspecified models, each of which is missing one additional parameter from the true model. Because the consequences of under-parameterization are more severe than over-parameterization (e.g. Maxwell & Delaney, 2004), this study will focus on the case of under-parameterized model misspecification. PPP's performance is evaluated by its ability to correctly detect misspecification in a misspecified model and to not falsely detect misspecification in a true model. DIC's performance is evaluated by its ability to select the true model over a misspecified model in a model comparison. As a benchmark, PPP's performance is shown alongside T_{ML}'s, and DIC's performance is shown alongside the likelihood ratio test (LRT). T_{ML} is the original fit statistic, testing the difference between the

sample and model-implied covariance matrix (Hu and Bentler, 1999). The LRT tests whether the more complex model significantly improves the fit of the simpler model given the change in degrees of freedom.

The population models used to generate data for this simulation study were chosen based on work by Paxton, Curran, Bollen, Kirby, and Chen (2001), and have since been used by Bollen, Harden, Ray, and Zavisca (2014), Chen, Curran, Bollen, Kirby, and Paxton (2008), and others in SEM simulation studies. Paxton et al. searched the literature for applications of SEM in psychology and sociology journals to find what they describe as the model most “commonly encountered in applied research” (p. 292). The path diagrams of the smaller and larger versions of the most common model appear in Figure 1, along with their population parameter values. The smaller model has 9 manifest variables (9MV model) and the larger has 15 manifest variables (15MV model).

Population values for parameters were chosen to provide specific population RMSEA values. The authors began by using the values found by Paxton et al., and adjusted them so that the same misspecifications would have the same population RMSEA in both the 9MV and the 15MV models. This makes it easier to compare across model sizes. The variances of the error terms were varied to provide total unit variance for each latent variable and each manifest variable. Communalities of manifest variables without cross-loadings are 0.40. All data were simulated in R (R Core Team, 2016).

Along with fitting the true model to the simulated data, five misspecified analysis models were fit to the data. A summary of these models is in Table 1. Each subsequent model is missing an additional parameter, increasing its population RMSEA and degrees of freedom. The first misspecified model, Model 2, represents only slight misspecification while Model 6 represents

severe misspecification. Each of these models were fit to data generated under Model 1 with sample sizes of 75, 150, 250, 500, and 1000. Mplus (Linda K Muthén & Muthén, 2012) was used to fit all models because it can estimate both ML-SEM and Bayesian SEM and it is user friendly. The syntax used to fit the models is in the supplementary material. All simulation conditions are listed in Table 2.

In the results, terms such as detection rates and model selection rates will be used in lieu of the traditional terms power and Type I error rates. This is because neither PPP nor DIC have significance tests where they can be categorized as being statistically significant or nonsignificant. Rather, PPP detection rates refer to the proportion of samples for which PPP was below a chosen cut-off, i.e. 0.10. If the model is truly misspecified, PPP<0.10 is a *correct detection*; if the model is the true model, PPP<0.10 is a *false detection*. False detection rates are comparable to T_{ML} Type I error rates, and correct detection rates are comparable to T_{ML} power.

To compare two models, their difference in DIC is calculated,

$$\Delta DIC = DIC_m - DIC_1, \tag{4}$$

where DIC_m refers to the DIC of the misspecified model and DIC_1 refers to the DIC of Model 1, the data generating model. DIC model selection rates refer to the proportion of samples for which ΔDIC is larger than a chosen cut-off, i.e. 7. *True model selection* occurs when $\Delta DIC > 7$; *misspecified model selection* occurs when $\Delta DIC < -7$. When DIC does not select a model, $-7 < \Delta DIC < 7$, it is up to the researcher to choose the more substantively meaningful model or the less complex model based on the rule of parsimony. Note that while DIC has three options (true model selection, misspecified model selection, no selection) LRT has only two options (reject simpler model, fail to reject simpler model). For this simulation, the true model is always

the more complex model. Consequently, LRT power rates are comparable to DIC true model selection rates. There is no LRT equivalent to DIC misspecified model selection rates.

Because PPP and DIC results are both represented as proportions of replications above or below some cut-off, standard errors can be computed to interpret their results. Any rate that is 2 standard errors (0.032) away from any given rate can be considered different.[a]

Simulation I: Establishment of Cut-Offs

The purpose of the first simulation is to evaluate the impact of model misspecification, sample size, and model size on the performance of PPP and DIC in order to establish cut-offs and other rules of thumb for their use. Mplus default priors were used for all parameters; these are provided in Table 3 for the reader's convenience. The PPP cut-offs of 0.05, 0.10, and 0.15 are shown alongside T_{ML} power and type I error rates, and DIC cut-offs of 3, 5, and 7 are shown alongside LRT power rates. PPP<0.01 was found to be too conservative, and so these results are not shown.

Results.

Posterior predictive p-values.

1,000 converged replications were used to compute results for each condition. ML convergence rates were lowest (79%-89%) at n=75 and >93% at $n = 150$ for the 9MV models. All convergence rates for the 15MV models were >99%. All Bayesian models converged; however, replications in which the calculation of pD was negative were thrown out (<4% of replications).

PPP detection rates for each cut-off and T_{ML} significance rates for all models appear in Table 4. PPP false detection rates decrease with sample size, increase with model size, and

[a]Standard error $(SE) = \sqrt{\frac{p(1-p)}{r}}$, where r is the number of replications and p is the proportion. Using a proportion of 0.50 yields the most conservative standard error, yielding a standard error of 0.016.

increase with larger cut-offs. All PPP false detection rates are ≤0.05 for the 9MV models. For the 15MV models, PPP false detection rates are ≤0.02 with the PPP<0.05 cut-off, ≤0.06 with the PPP<0.10 cut-off, and ≤0.11 with the PPP<0.15 cut-off. All T_{ML} Type I error rates are ≤0.06 with the 9MV model, but as high as 0.21 with the 15MV model at $n = 75$. These results show that the PPP<0.15 cut-off may be inappropriate for the larger model; furthermore, T_{ML} may be inappropriate for the larger model with sample sizes less than 500.

PPP correct detection rates increase with sample size, increase with model size, increase with model misspecification, and increase with larger cut-offs. In general, its behavior appears to be similar to T_{ML}. For both the 9MV and 15 MV models, PPP<0.15 has correct detection rates closest to T_{ML} power rates. However, given the increased false detection rates with PPP<0.15 for the 15MV model, it is recommended that that cut-offs be decreased as model size increases.

Deviance information criteria.

A comparison of DIC model selection rates for each cut-off and LRT power rates for all models are in Table 5. DIC misspecified model selection rates decrease with sample size, decrease with model size, decrease with increased comparison model misspecification, and decrease with larger cut-offs. Performance in evaluating the smaller models is inconsistent at small sample sizes. Elimination of replications with negative pDs improved performance, but did not entirely correct it. For the 9MV models, ΔDIC>7 is the only cut-off with all misspecified model selection rates ≤0.05. All ΔDIC>5 misspecified model selection rates are ≤0.05 with $n \geq 150$, and all ΔDIC>3 misspecified model selection rates are ≤0.05 with $n \geq 250$. For the 15MV models, all DIC misspecified model selection rates are ≤0.05.

DIC correct model selection rates increase with sample size, increase with model size, increase with increased comparison model misspecification, and decrease with larger cut-offs.

For both the 9MV and 15MV models, ΔDIC>3 has true model selection rates closest to LRT power rates. However, this cut-off should only be used with larger sample and/or model sizes.

Conclusions.

The results from these simulations indicate that PPP and DIC are both heavily impacted by sample size, model size, and model misspecification. PPP is better able to detect misspecification and DIC is better able to choose the correct model as sample size increases and as model size increases. Furthermore, DIC's ability to not select the misspecified model improved as sample size increased, becoming lower than 0.05 once n=250. PPP's false detection rates were all lower than 0.05 with cut-offs ≤0.10. As with T_{ML}, in larger samples PPP will always reject a model even with minimal misspecification. In practical data analysis, the true model will likely not be evaluated. Therefore, PPP may not be useful in large samples unless the true model is among the candidate models. Alternatively, DIC showed inconsistent performance with n<250 and should not be used in small sample sizes. As sample size increases, DIC's performance improves.

Larger PPP cut-offs corresponded most similarly to T_{ML} performance, and small DIC cut-offs corresponded most similarly to LRT performance. However, these are also the cut-offs that had too high false detection rates and misspecified model selection rates, respectively. In practical data analysis, sample size and model size should be taken into account when evaluating PPP and DIC. For the particular models tested here, PPP<0.15 is recommended for the 9MV models and PPP<0.10 is recommended for the 15MV models; ΔDIC>7 is recommended for the 9MV models unless sample size is large, and ΔDIC>3 is recommended for the 15MV model. In the second simulation, only the 9MV model is used. Therefore, PPP<0.15 and ΔDIC>7 are used to calculate the results appearing in the remainder of this document.

Simulation II: Influence of Priors

The purpose of this simulation is to evaluate the impact of prior choice on the performances of PPP and DIC. Specifically, this simulation study will assess how priors on factor loadings will affect PPP detection rates and DIC model selection rates. It is well-known that prior choice can affect parameter estimates and substantive conclusions (van de Schoot & Depaoli, 2014; Gelman, 2006; Gelman & Shalizi, 2013; Johnson, 2013; Seaman III et al., 2012), but it is less clear what impact prior choice has on Bayesian model evaluation. Some simulation studies have shown PPP to be prior-dependent (Asparouhov & Muthén, 2010a), while theoretical work suggests that PPP is robust to small modification on the prior (De la Horra & Teresa Rodriguez-Bernal, 2003; Gelman et al., 1996). In contrast, it is believed that DIC is strongly sensitive to prior choice, in that decreasing prior variance decreases DIC (Spiegelhalter, Best, Carlin, & Linde, 2014b; Ward, 2008).

The aim of this simulation is to assess the sensitivity of PPP and DIC to changes in prior accuracy in a Bayesian SEM analysis. For the purposes of demonstration, only the factor loadings will be given an informative prior, while the other parameters will keep the same default priors used in the previous study. This approach was chosen because researchers often have interest in only a subset of parameters, and it is likely that previous studies will provide some information about the factor loadings. Because Mplus currently only allows specification of normal priors for factor loadings, only the hyperparameters will be changed.

Three priors, Prior 2: N(0.43,0.04), Prior 3: N(0.43,0.01), and Prior 4: N(0.43,0.005), are compared to the default prior, Prior 1: N(0, ∞). These three priors cover the population parameter range of the factor loadings within 1 standard deviation (SD), 2 SDs, and 3 SDs, respectively. Therefore, it is predicted that Prior 2 would have the best performance while Prior 4

would have the worst. The hypothetical set-up for this experiment could be that a researcher has found several previous studies using these variables that provide some knowledge of how each latent variable is measured. These studies have shown mean standardized factor loadings to be around 0.43, however they're unsure of how informative to make the priors.

Results.

Posterior predictive p-values.

All replications converged for each condition. PPP detection rates for each prior are shown in Table 6; all rates are the proportion of samples with PPP$<$0.15. As expected, PPP false detection rates increase with the increasingly inaccurate priors. Only Priors 1 and 2's false detection rates are all ≤ 0.05, demonstrating that the chosen prior distribution must cover the population parameter range within 1 SD to obtain reliable results. Correct detection rates are higher for Priors 3 and 4 in detecting minor model misspecifications, and similar across priors when evaluating models with severe misspecification.

Deviance information criteria.

DIC model selection rates for each prior are in Table 7; all rates are the proportion of samples with ΔDIC>7. As expected, Prior 2 has the best performance and Prior 4 has the worst. When comparing Models 1 and 2, Model 2 is selected in up to 52% of replications when n=150 using Prior 4; Model 2 is never selected when using Prior 2. In fact, the highest misspecified model selection rate using Prior 2 is 3% across conditions. Across all priors, misspecified model selection rates are all ≤0.05 with $n \geq 500$. True model selection rates decrease with increasingly inaccurate priors. One of the larger gaps appears when comparing Models 1 and 5. Model 1 is selected in 69% of replications at $n = 75$ using Prior 2; Model 1 is selected in only 33% of replications when using Prior 4.

Conclusions.

The aim of this simulation was to assess the impact of choice of prior. It was shown that using inaccurate priors negatively impacted both PPP and DIC in terms of both selecting the true model and detecting a misspecified model. The difference in performance between the default prior, Prior 1, and Prior 2 were generally larger for DIC than for PPP, suggesting that DIC is more sensitive to prior selection than is PPP.

Discussion

The Bayesian framework offers a flexible and powerful approach to SEM estimation. One major challenge that continues to limit the utility of Bayesian SEM is the lack of guidelines for evaluating model fit and model comparison. PPP and DIC are now available through Mplus and WinBUGS, but their performance has not been widely evaluated and guidelines for their use have not been provided. Without practical guidelines, Bayesian SEM users cannot appropriately use and interpret them in their own data analysis.

The broad goals of this project were to evaluate PPP and DIC to identify the conditions of a data analysis that may affect their performance in order to provide guidelines for their use in practical analysis. Specifically, the simulation studies in this report examined the impacts of sample size, model size, model misspecification, and prior choice on PPP detection rates and DIC model selection rates. Model size was defined by the number of manifest variables, model misspecification was defined by RMSEA, and prior accuracy was defined by prior coverage of the population parameter space. The choice of RMSEA and of specific priors were solely for demonstration purposes to show how the performances of PPP and DIC are impacted as misspecification or prior accuracy gets worse. The definitions of “worse” for either were not

important, because the trend in results were more of interest here than the rates themselves. Similar trends in results are expected with other definitions.

The results from the simulation studies showed that both PPP detection rates and DIC true model selection rates increased with population RMSEA, sample size, and model size. PPP and DIC were found to be less powerful than their ML counterparts, T_{ML} and LRT, respectively, but were in general comparable. PPP false detection rates were lower than T_{ML} Type I error rates in most conditions. PPP$<$0.15 had correct detection rates most comparable to T_{ML} and maintained false detection rates below 5% when evaluating the true model among the smaller models, but a lower cut-off is required for the larger models to maintain a low false detection rate. ΔDIC>7 had the lowest true model selection rates but maintained misspecified model selection rates below 5% for the smaller models; a smaller cut-off could be used for large samples and/or larger models.

In evaluating the impact of prior choice, it was found that DIC was slightly more sensitive to changes in prior than PPP, but both performances suffered greatly when using an inaccurate prior. For PPP, the performances of the default prior and the accurate informative prior were similar; for DIC, the accurate informative prior outperformed the default prior. By n=500, prior influence of even the most informative prior had dissipated for both PPP and DIC.

Because the calculation of DIC was inconsistent in samples smaller than 250, it is recommended to only use DIC in larger sample sizes. Alternatively, PPP may not be useful in large samples because it will always detect misspecification in large samples even when the model is minimally misspecified. In smaller samples, PPP had high rates of detecting misspecification in the true model only when an informative prior was inappropriate. These results show that PPP may be able to be used for prior selection in practical data analysis. Future

studies would be required, however, before any practical guidelines could be established for this use of PPP. These comparisons were not done with DIC in the current analysis, and therefore are out of the scope of the current project.

This paper provides the first large-scale simulation study evaluating the performances of PPP and DIC. As such, there are many limitations to the current work, the most severe being generalizability. Because the purpose of this study was to give an overview of the performances of PPP and DIC and to set a foundation for future work, more in-depth research in a particular area would be required before any conclusive recommendations or guidelines could be made. Future studies should evaluate PPP and DIC in alternative models, misspecifications, priors, and data distributions. There also needs to be future work in using PPP and DIC on categorical data, multilevel data, missing data, and in models with mean structure. Some specific limitations that warrant future research are discussed below.

First, only one model type was evaluated in this study. This model was chosen for being the most commonly used in social science SEM applications, but the use of one model severely limits the scope of the recommendations provided here. In addition, only one type of misspecification, under-parameterization, was used here. Second, in evaluating the performance of DIC, misspecified models were only compared to the true model. In practice, the true model would not be among the competing models. Future research should examine DIC's performance in selecting among misspecified models. Third, only four prior configurations were tested here. These were sufficient to show the sensitivity of PPP and DIC to prior choice, but a much larger simulation study should be conducted to broadly evaluate the impact that prior has on each. There also needs to be future work to establish guidelines on whether and how they could be used in a sensitivity analysis or in prior selection, for example.

Fourth, only normally distributed data were evaluated here, and were only evaluated using the normal likelihood-based model. Future studies should examine the impact of nonnormality, and examine the performances of PPP and DIC in a robust Bayesian SEM analysis.

In addition to these limitations, it also seems necessary at this point to remind readers of the dangers of using specific cut-offs for fit indices in general. This has been discussed in many places (Chen et al., 2008; Fan & Sivo, 2007; Kenny & McCoach, 2003; Marsh, Hau, & Wen, 2004) and so will not be reproduced here, except to say that if the model being analyzed is not reasonably close in characteristic to that analyzed here that the performance of PPP and DIC may differ substantially. For added insurance, the two-index presentation strategy (Hu & Bentler, 1999) should be employed in Bayesian SEM as it is in ML-SEM. Because PPP and DIC provide different information, reporting both would provide a more complete picture of the models being tested. It is also important to keep in mind that PPP and DIC are merely additional tools to help guide a researcher in any particular study. The traditional methods of cross-validation and replication should always be applied to assess a given model.

Until future research can be conducted, the results of this study show that PPP and DIC can be used for model evaluation in Bayesian SEM if the models and conditions of the data analysis are similar to those investigated here. Based on the results from the simulation studies, a summary of the recommended cut-offs for these models is shown in Table 8. Through these results and recommendations, Bayesian SEM can become a more accessible option for social science researchers to have more flexibility in their SEM analysis.

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List of Tables and Figures

Table 1. True and misspecified models, their RMSEA, and degrees of freedom.

Model	Description of Misspecification	Pop. RMSEA	Smaller Model df	Larger Model df
1	True Model	0.00	22	85
2	Missing one cross-loading	0.03	23	86
3	Missing two cross-loadings	0.04	24	87
4	Missing three cross-loadings	0.05	25	88
5	Missing three cross-loadings and one regression pathway	0.08	26	89
6	Missing three cross-loadings, and both regression pathways	0.10	27	90

Notes. The path diagram for the smaller model Model 1 is shown in Figure 1. The larger model is the same but with additional 2 manifest variables loading onto each latent variable. Pop. RMSEA= $\sqrt{\frac{F_{ML}}{df}}$.

Table 2. Simulation conditions.

Factor	Levels
Model Size (# MVs)	9, 15
PPP cut-offs	0.05, 0.10, 0.15
ΔDIC cut-offs	5, 7, 9
Sample Sizes	75, 150, 250, 500, 1000
Population RMSEA[a]	0 (True), 0.028, 0.038, 0.050, 0.080, 0.100
Priors for λ's	$1: N(0, \infty), 2: N(0.43, 0.040), 3: N(0.43, 0.010), 4: N(0.43, 0.005)$
# Replications/ Condition	1000

[a]The analysis models are listed in Table 1. MVs=manifest variables.

Table 3. Prior distributions in Mplus

Parameter Type	Prior Distributions Available	Default Prior
λ	Normal	$N(0, \infty)$
β	Normal	$N(0, \infty)$
ϵ	Inverse Gamma	$IG(-1,0)$
ζ	Inverse Wishart	$IW(0, -p - 1)$

Notes. The only parameters listed here are those used in this study. For available distributions and default settings of priors on other types of parameters, see the Mplus User's Manual (L. K. Muthén & B.O. Muthén, 2012).

Table 4. PPP detection rates at different cut-offs.

Model	n	Smaller Model (9 MVs)				Larger Model (15 MVs)			
		PPP<0.05	PPP<0.10	PPP<0.15	T_{ML}	PPP<0.05	PPP<0.10	PPP<0.15	T_{ML}
1	75	0.01	0.02	0.05	0.06	0.02	0.06	0.11	0.21
	150	0.01	0.02	0.04	0.05	0.02	0.05	0.10	0.09
	250	0.01	0.01	0.04	0.05	0.01	0.03	0.07	0.07
	500	0.00	0.01	0.03	0.05	0.02	0.04	0.09	0.06
	1000	0.00	0.02	0.05	0.06	0.02	0.03	0.07	0.06
2	75	0.01	0.04	0.08	0.09	0.05	0.10	0.19	0.30
	150	0.02	0.05	0.09	0.11	0.09	0.18	0.27	0.28
	250	0.03	0.08	0.13	0.16	0.15	0.29	0.44	0.43
	500	0.10	0.20	0.30	0.32	0.54	0.70	0.80	0.77
	1000	0.33	0.50	0.65	0.67	0.96	0.98	0.99	0.99
3	75	0.02	0.06	0.11	0.12	0.08	0.16	0.25	0.40
	150	0.04	0.09	0.15	0.18	0.21	0.34	0.47	0.48
	250	0.07	0.16	0.27	0.31	0.48	0.62	0.73	0.72
	500	0.34	0.49	0.60	0.62	0.94	0.97	0.99	0.99
	1000	0.83	0.92	0.95	0.96	1.00	1.00	1.00	1.00
4	75	0.03	0.09	0.14	0.18	0.17	0.28	0.40	0.53
	150	0.11	0.20	0.29	0.32	0.48	0.65	0.75	0.76
	250	0.22	0.39	0.51	0.58	0.82	0.91	0.95	0.94
	500	0.75	0.87	0.93	0.93	1.00	1.00	1.00	1.00
	1000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	75	0.16	0.31	0.42	0.51	0.62	0.77	0.85	0.92
	150	0.58	0.76	0.85	0.86	0.99	1.00	1.00	1.00
	250	0.92	0.96	0.98	0.98	1.00	1.00	1.00	1.00
	500	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	1000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6	75	0.42	0.61	0.73	0.78	0.95	0.98	0.99	1.00
	150	0.92	0.96	0.98	0.99	1.00	1.00	1.00	1.00
	250	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	500	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	1000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Notes. Descriptions of these models are in Table 1. PPP results for Model 1 are false detection rates and T_{ML} results are Type I error rates. For the remaining models, PPP results are correct detection rates and T_{ML} results are power rates. All results are based on 1,000 converged replications. MVs=manifest variables.

Table 5. DIC model selection rates at different cut-offs

Smaller Model (9 MVs)											
		Model 2		Model 3		Model 4		Model 5		Model 6	
n	Criterion	M1	M2	M1	M3	M1	M4	M1	M5	M1	M6
75	ΔDIC>3	0.28	0.10	0.30	0.20	0.38	0.20	0.77	0.04	0.90	0.01
	ΔDIC>5	0.19	0.03	0.20	0.06	0.27	0.08	0.68	0.01	0.84	0.01
	ΔDIC>7	0.14	0.02	0.14	0.03	0.21	0.02	0.58	0.00	0.79	0.00
	LRT	0.24		0.28		0.41		0.85		0.97	
150	ΔDIC>3	0.31	0.08	0.38	0.11	0.60	0.09	0.96	0.01	1.00	0.00
	ΔDIC>5	0.20	0.03	0.26	0.01	0.48	0.03	0.92	0.01	1.00	0.00
	ΔDIC>7	0.14	0.03	0.20	0.00	0.37	0.00	0.89	0.01	1.00	0.00
	LRT	0.37		0.52		0.71		0.99		1.00	
250	ΔDIC>3	0.45	0.02	0.62	0.03	0.85	0.01	1.00	0.00	1.00	0.00
	ΔDIC>5	0.31	0.01	0.46	0.01	0.76	0.00	1.00	0.00	1.00	0.00
	ΔDIC>7	0.19	0.01	0.35	0.00	0.68	0.00	1.00	0.00	1.00	0.00
	LRT	0.55		0.74		0.90		1.00		1.00	
500	ΔDIC>3	0.76	0.00	0.93	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	ΔDIC>5	0.63	0.00	0.85	0.00	0.99	0.00	1.00	0.00	1.00	0.00
	ΔDIC>7	0.50	0.00	0.77	0.00	0.98	0.00	1.00	0.00	1.00	0.00
	LRT	0.81		0.96		1.00		1.00		1.00	
1000	ΔDIC>3	0.96	0.00	1.00	0.00	1.00	0.00	0.99	0.01	1.00	0.00
	ΔDIC>5	0.92	0.00	1.00	0.00	1.00	0.00	0.99	0.01	1.00	0.00
	ΔDIC>7	0.87	0.00	1.00	0.00	1.00	0.00	0.99	0.01	1.00	0.00
	LRT	0.98		1.00		1.00		1.00		1.00	
Larger Model (15 MVs)											
		Model 2		Model 3		Model 4		Model 5		Model 6	
n	Criterion	M1	M2	M1	M3	M1	M4	M1	M5	M1	M6
75	ΔDIC>3	0.44	0.00	0.61	0.05	0.86	0.01	1.00	0.00	1.00	0.00
	ΔDIC>5	0.32	0.00	0.49	0.00	0.78	0.00	1.00	0.00	1.00	0.00
	ΔDIC>7	0.22	0.00	0.39	0.00	0.70	0.00	0.99	0.00	1.00	0.00
	LRT	0.57		0.74		0.90		1.00		1.00	
150	ΔDIC>3	0.77	0.00	0.93	0.00	0.99	0.00	1.00	0.00	1.00	0.00
	ΔDIC>5	0.65	0.00	0.87	0.00	0.99	0.00	1.00	0.00	1.00	0.00
	ΔDIC>7	0.53	0.00	0.80	0.00	0.97	0.00	1.00	0.00	1.00	0.00
	LRT	0.88		0.97		1.00		1.00		1.00	
250	ΔDIC>3	0.97	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	ΔDIC>5	0.91	0.00	0.99	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	ΔDIC>7	0.86	0.00	0.99	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	LRT	0.98		1.00		1.00		1.00		1.00	
500	ΔDIC>3	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	ΔDIC>5	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	ΔDIC>7	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	LRT	1.00		1.00		1.00		1.00		1.00	
1000	ΔDIC>3	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	ΔDIC>5	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	ΔDIC>7	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	LRT	1.00		1.00		1.00		1.00		1.00	

Notes. Descriptions of each model are in Table 1. ΔDIC is defined in Eq. 2. Each pair of columns shows true model selection rates under "M1" and misspecified model selection rates under the alternative model column heading.

Table 6. PPP detection rates for each prior.

Model	n	Prior 1	Prior 2	Prior 3	Prior 4
1	75	0.05	0.05	0.27	0.55
	150	0.04	0.04	0.29	0.78
	250	0.04	0.03	0.17	0.76
	500	0.03	0.02	0.09	0.60
	1000	0.05	0.04	0.07	0.27
2	75	0.08	0.08	0.26	0.49
	150	0.09	0.08	0.24	0.64
	250	0.13	0.10	0.24	0.66
	500	0.30	0.27	0.38	0.75
	1000	0.65	0.64	0.71	0.87
3	75	0.11	0.08	0.19	0.33
	150	0.15	0.14	0.27	0.54
	250	0.27	0.27	0.37	0.63
	500	0.60	0.57	0.65	0.83
	1000	0.95	0.95	0.95	0.97
4	75	0.14	0.11	0.19	0.27
	150	0.29	0.29	0.37	0.56
	250	0.51	0.48	0.57	0.71
	500	0.93	0.92	0.93	0.97
	1000	1.00	1.00	1.00	1.00
5	75	0.42	0.37	0.47	0.57
	150	0.85	0.84	0.88	0.92
	250	0.98	0.98	0.98	0.99
	500	1.00	1.00	1.00	1.00
	1000	1.00	1.00	1.00	1.00
6	75	0.73	0.67	0.76	0.82
	150	0.98	0.98	0.99	1.00
	250	1.00	1.00	1.00	1.00
	500	1.00	1.00	1.00	1.00
	1000	1.00	1.00	1.00	1.00

Notes. Descriptions of each model are in Table 1. PPP results for Model 1 are false detection rates and T_{ML} results are Type I error rates. For the remaining models, PPP results are correct detection rates and T_{ML} results are power rates. Priors are described in Table 2.

Table 7. DIC model selection rates for each prior.

		Model 2		Model 3		Model 4		Model 5		Model 6	
n	Prior	M1	M2	M1	M3	M1	M4	M1	M5	M1	M6
75	Prior 1	0.19	0.03	0.20	0.06	0.27	0.08	0.68	0.01	0.84	0.01
	Prior 2	0.12	0.00	0.15	0.00	0.22	0.03	0.69	0.00	0.87	0.00
	Prior 3	0.10	0.04	0.09	0.30	0.11	0.42	0.45	0.13	0.72	0.05
	Prior 4	0.11	0.11	0.08	0.45	0.08	0.59	0.33	0.26	0.62	0.09
150	Prior 1	0.20	0.03	0.26	0.01	0.48	0.03	0.92	0.01	1.00	0.00
	Prior 2	0.12	0.00	0.29	0.00	0.52	0.01	0.95	0.00	1.00	0.00
	Prior 3	0.06	0.29	0.14	0.28	0.26	0.25	0.81	0.03	0.98	0.00
	Prior 4	0.05	0.52	0.06	0.64	0.11	0.60	0.58	0.13	0.91	0.02
250	Prior 1	0.31	0.01	0.46	0.01	0.76	0.00	1.00	0.00	1.00	0.00
	Prior 2	0.24	0.00	0.56	0.00	0.80	0.00	1.00	0.00	1.00	0.00
	Prior 3	0.14	0.12	0.32	0.09	0.58	0.06	0.99	0.00	1.00	0.00
	Prior 4	0.06	0.45	0.09	0.52	0.21	0.42	0.90	0.01	1.00	0.00
500	Prior 1	0.63	0.00	0.85	0.00	0.99	0.00	1.00	0.00	1.00	0.00
	Prior 2	0.64	0.00	0.88	0.00	0.99	0.00	1.00	0.00	1.00	0.00
	Prior 3	0.58	0.00	0.81	0.00	0.98	0.00	1.00	0.00	1.00	0.00
	Prior 4	0.41	0.05	0.53	0.08	0.84	0.02	1.00	0.00	1.00	0.00
1000	Prior 1	0.92	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	Prior 2	0.92	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	Prior 3	0.89	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
	Prior 4	0.84	0.00	0.97	0.00	1.00	0.00	1.00	0.00	1.00	0.00

Notes. Descriptions of each model are in Table 1. Each pair of columns shows true model selection rates under "M1" and misspecified model selection rates under the alternative model column heading. The priors are described in Table 2.

Table 8. Summary of recommendations.

Sample Size	Model Size	Recommended Cut-Off	
75	9 MVs	PPP<0.15	ΔDIC>7
	15 MVs	PPP<0.10	ΔDIC>3
150	9 MVs	PPP<0.15	ΔDIC>5
	15 MVs	PPP<0.10	ΔDIC>3
≥250	9 MVs	PPP<0.15	ΔDIC>3
	15 MVs	PPP<0.10	ΔDIC>3

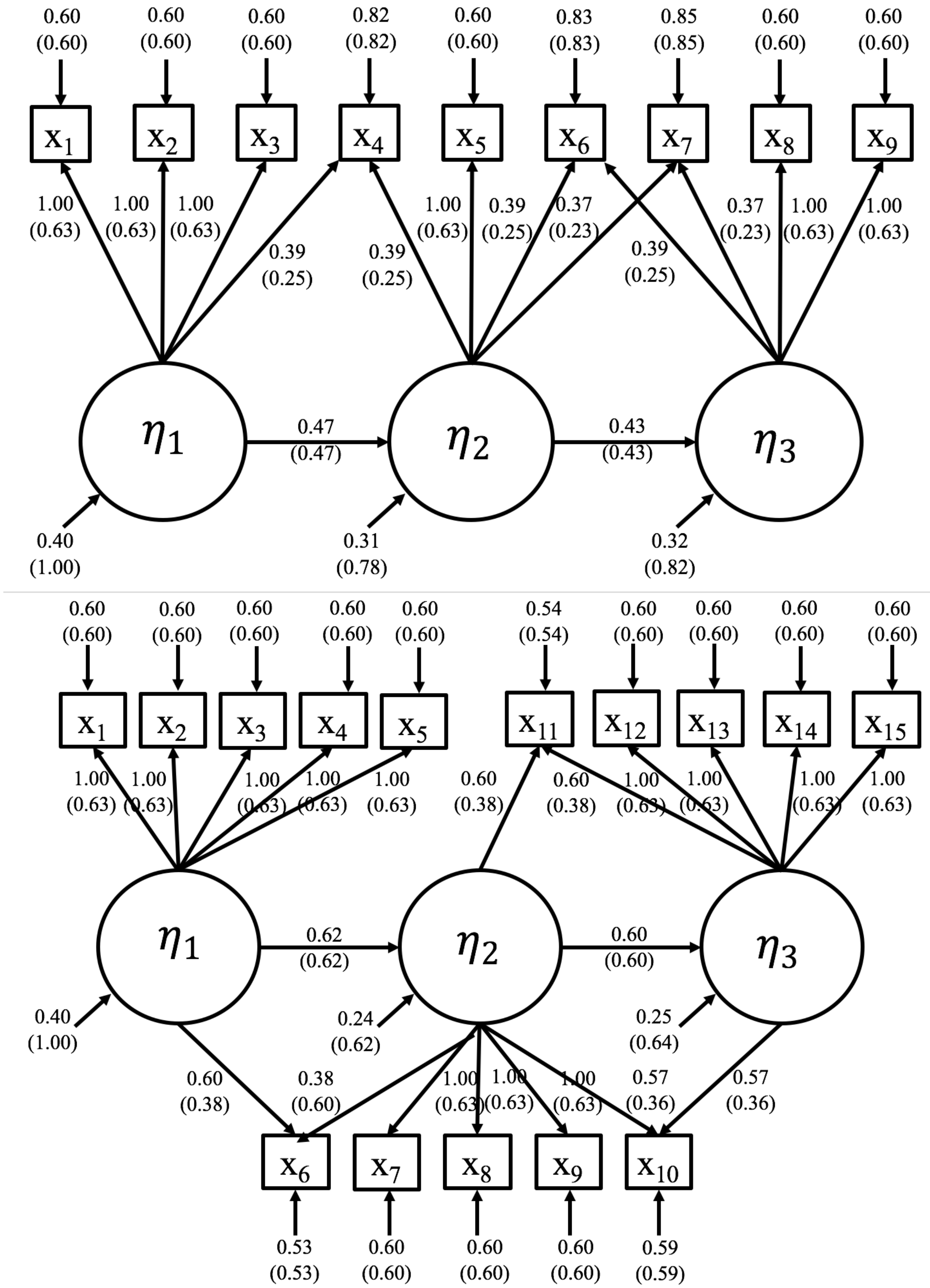

Figure 1. The data generating models and their unstandardized (standardized) population parameter values.