**Reply to referee 1**

I thank the referee for a thoughtful review of my paper. I have tried to thoroughly address all of the referee's points, which I discuss in detail below.

Comment:

The answers have implications for where we would expect pricing to go in the future, and possibly for governmental policy and regulations. The results suggest that solar panels are not commodities, and are consistent with asymmetric information.

However, the authors hedge at the end, saying that maybe they will be commodities in the future. I found this last part a little weak – I would suggest the authors discuss this in a richer way, as it seems to poke the air out of their bubble at the very end of the paper.

Answer:

I agree that this point deserves a richer discussion. In the revised version, I conclude with the following two paragraphs (p.25):

The market for solar panels and solar panel systems is however still young and dynamic. One of the advantages of the linear mixed-effects models and the hierarchical models is that we can also get an idea of the degree of differentiation in quality between different manufacturers. Only about 20% of producers accounted for the worst quality panels, while the majority of panels had similar quality. If low-quality producers either are forced to exit the market or improve their quality to match standards in the industry, then it is possible that solar panels could indeed become commodities in the future.

However, optimism should be tempered by both theory and experience from other industries. Markets that are subject to informational problems have a tendency to experience stasis. As Akerlof (1970) notes, poor quality producers will tend to push out high quality producers in the presence of asymmetric information. In a long-term study of the used car market in Switzerland, Emons et. al. (2009) find evidence of sustained quality uncertainty among buyers. Evidence of long-term quality uncertainty is also found in the market for business aircraft Gilligan (2004). The market for solar panels may long be characterised by producers differentiated by quality. In consequence, the buyers of solar panels will need to take steps to ensure high quality such as paying a premium for panels from a reputed producer or making use of engineering firms specialising in certifying panel quality.

Comment:

Equation 1: please define all symbols before the equation is presented. Define the symbols precisely – that is many of the symbols have subscripts of s[i] that are never defined as far as I could see, and are certainly not defined anywhere near the equation. Also, prod is never defined. Similarly, it would be helpful to have a table that defines all symbols, such as mu\_a and so on.

Answer:

A good suggestion. I now present tables with detailed definitions of all symbols alongside the presentation of each model. Please see Tables 2,3 and 5 on P.10, P.11 and P.17.

Comment:

Figures 12-15: please make the fonts of the labels bigger, especially the label of the y-axis.

Answer:

I have increased the size of the font.

Comment:

In the conclusion it says: “It appears that a relatively small tail of producers accounted for the worst quality panels, while the majority of panels had similar quality.” It would be helpful to the reader to quantify this in some way.

Answer:

I have now changed this sentence to say: "About 20% of producers accounted for the worst quality panels, while the majority of panels had similar quality."

**Reply to Referee 2**

Comment:

The paper is an applied statistics paper with financial/economics background (something like financial econometrics). The focus is on testing for properties of a market. As far as I can see, any decision making perspective is missing, which would be important, given that EJOR is an OR journal. Moreover there seems to be no real methodological novelty in this paper. Just applying some more or less standard approaches to some question is not enough. (Maybe the paper fits better into some financial/financial econometrics journal, where the analyzed economic question might be seen as a novelty, suiting into the main topics of the journal)

Answer:

I thank the reviewer for his comments, and I take their criticism seriously. I agree that in my initial submission, I have not done enough to communicate both how my paper contributes to understanding decision making and how it fits into the broader operations research literature, as well as highlighting the methodological novelty in my article.

On page 2, I have expanded the discussion around the implications of whether solar panels are commodities. In particular, I discuss the importance this has for procurement of solar panels:

Determining whether a product is a commodity is of more than just theoretical importance. Historically, the commodification of goods was a necessary condition for the establishment of sophisticated financial markets for those goods. A well-documented example: The invention of grain elevators for mixing and standardising grain was a necessary precursor to the establishment of a futures markets with receipts of delivery traded on the Chicago Board of Trade (Cronon, 1992). The abstraction between producer and end purchaser of goods was necessary for the functioning of these markets. A trader could fulfil a promise to deliver grain of a certain grade by simply buying it on the market or with cash settlement, rather than having produced it oneself.

An important differentiating characteristic between solar panels is the quality of these solar panels. This can be measured as both the failure rate of these panels as well as the degree of degradation of the panels over time. If there were significant differences in quality between manufacturers, then this has implications for the structure and development of the solar panel market. Manufacturers with superior quality could differentiate themselves and extract a premium in the market. A reputation for quality among established manufacturers could also act as a barrier to entry, thereby reducing long-term pricing pressure.

From the perspective of a purchasing manager responsible for procuring solar panels, whether panels can be considered a commodity is of great importance. If panels are known to be commodities with standardised quality and similar pricing, then the decision for purchasing manager is substantially simplified. They need only to decide on the observable form factor, for example dimension and capacity. In addition, purchasing managers responsible for large projects with long lead times could make use of forward markets to hedge price movements. On the other hand, if solar panels are known to vary significantly by quality, then the decision becomes substantially more complex and costly. Purchasing managers would need to weigh the price of panels against expected quality. They may also need to make use of specialised engineering firms that test and certify panel quality. Since the purchasing decision is likely to be linked to a specific manufacturer, the purchasing manager is subject to risks such as bankruptcy or other supply disruption associated with that firm.

I have also expanded the discussion of the hierarchical Bayesian modelling to include an extended discussion of its core usage in the operations research field and commonalities with my own research subject (p.4-5):

As a solution, I use a Bayesian hierarchical model estimated using Markov Chain Monte Carlo (MCMC) simulation techniques. Bayesian hierarchical models have long been one of the primary tools in statistical decision theory (Bergen, 1985) and this form of modelling is increasingly common in operations research and management science. One of the main advantages is superior out-of-sample predictive properties with data with distinct groupings. Recent advances in computation have also allowed for the construction and simulation of increasingly complex models. In particular, I use the Stan probabilistic programming language (Stan Development Team, 2014) that makes use of Hamiltonian Markov Chain Monte Carlo (MCMC) (MacKay, 2003) and a No-U-Turn sampler (Homan and Gelman, 2014). Unlike earlier MCMC simulation routines, notably Gibbs sampler, Hamiltonian MCMC is able to reach convergence even with models, like the one I present in this article, with multiple hierarchies. Importantly, with the Hamiltonian MCMC routine, it is not necessary to use conjugate distributions, opening up to a wider variety of choice of prior distributions (Kruschke, 2014).

In part due to increasing computational tractability, Bayesian hierarchical models have recently become a common and useful tool in the operations research field. A common application is to incorporate expert opinion into quantitative decision models (Rufo et al., 2010; Szwed et al., 2006; Utkin, 2006). In this application, the Bayesian hierarchical model is flexible enough to aggregate the information of the expert opinions while also being able to explicitly handle and propagate the uncertainty in these opinions. Hierarchical models have also been used to identify default risk among lenders and improve credit scoring models (Liu et al., 2015; Bhattacharya et al., 2019). In this context, the hierarchical Bayesian models are found to provide superior out-of-sample prediction for the censored sample of the data. Other operations research related applications include a fund manager's portfolio selection problem (Soyer and Tanyeri, 2006; Bodnar et al., 2017) and conjoint analysis in operations management (Karniouchina et al., 2009; Gensler et al., 2012). A commonality among all these applications is the need to aggregate information from heterogenous groups without over-fitting the data with many fixed effects.

I have also added additional discussion in my presentation of hierarchical Bayesian model (p.15-16):

Bayesian methods making use of MCMC simulation are still emerging and this is an active field of research in both the statistical sciences and operations research fields. It is worth spending a moment to motivate their use in this case over asymptotic methods that are more common. The main reason for using the Bayesian model is the flexible treatment it allows for modelling the inherent hierarchy of the data and allowing for partial pooling in estimation.

In a hierarchical model, lower-level parameters within a certain group are themselves modelled as coming from a distribution characterised by “meta-parameters”. Thus, the estimated group-level parameters are a weighted function of both the observations within the group as well as the full set of observations in the data-set. For example, the estimated mean parameter on a group with a few, outlying observations would be pulled towards the full sample mean. This partial pooling also serves as a natural form of parameter shrinkage, which mostly eliminates the need for using corrections for multiple comparisons in inference (Gelman and Hill, 2006).

With a Bayesian multilevel model, I also have greater flexibility in specifying the model without having to rely on assumptions like constant group-level variances and a Gaussian noise distribution. Because Bayesian simulation techniques result in an estimate of the full joint probability distribution of the model, the inference has the potential to be more informative than the typical point estimates and p-values of the standard hypothesis testing frameworks (Kruschke, 2014).

Another advantage is that the posterior distributions of the parameters have a natural and direct interpretation as probabilities, as opposed to standard hypothesis testing where the concepts of p-values and significance are often ill-defined. See Kruschke (2014) or Gelman et al. (2013) for further discussion.

Hierarchical models estimated using Bayesian techniques have some nice theoretical properties. However, the main advantages to using the Bayesian techniques here are practical. Models of nearly arbitrary richness can be estimated, with computational time and available data being the main constraints. Inference is also well-defined and exact.

In the concluding remarks I also add a short discussion about the methodological contributions of the paper:

The use of Bayesian MCMC simulation techniques in this article also provides an illustrative example of the use and usefulness of a powerful emerging toolset. The Bayesian frameworks and recently developed software such as Stan provide major practical and theoretical advantages over many traditional statistical methods used in operations research and decision science. These methods and tools are also increasingly accessible to practitioners. Kruschke (2014), McElreath (2015), Gelman et al. (2013) and Stan Development Team (2014) provide accessible and thorough introductions and guides.

**Reply to referee 3**

I thank the referee for their thoughtful critique. I have tried to address all of the referee's suggestions, which I detail below.

Comment 1. This article should explain the definition of the commodity. Then explain the relevance of the commodity definition and the results of this article.

I agree, and I have substantially altered the discussion of the importance of commodification the introduction. In particular, I write (p.1):

More formally, a commodity is generally defined by a certain degree of fungibility. That is, the good from a certain producer will be largely interchangeable with the good of another producer. Already in 1873 the German economist A.E.F. Schäffle distinguished between a popular understanding of a commodity as a material input in manufacturing, to the scientific understanding as "exchangeable material goods" (Menger, 2007). Despite the relative simplicity of this definition, (Gordon and Hannesson, 1999) show the difficulty in practice of determining whether a product is in fact a commodity. The root problem is that a good can be differentiated in a host of ways, some of which are difficult to observe at the time of transaction.

Determining whether a product is a commodity is of more than just theoretical importance. Historically, the commodification of goods was a necessary condition for the establishment of sophisticated financial markets for those goods. A well-documented example: The invention of grain elevators for mixing and standardising grain was a necessary precursor to the establishment of a futures markets with receipts of delivery traded on the Chicago Board of Trade (Cronon, 1992). The abstraction between producer and end purchaser of goods was necessary for the functioning of these markets. A trader could fulfil a promise to deliver grain of a certain grade by simply buying it on the market or with cash settlement, rather than having produced it oneself.

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Comment 2. The abstract and conclusion need to be written more briefly and clearly what contribution of the manuscript you have.

Answer:

I agree. I have shortened the abstract, and in addition to stating my findings, I have added the following statement highlighting the methodological contribution:

"Methodologically, the article demonstrates a novel application of Bayesian hierarchical regression models that have been commonly used in operations research and the decision sciences."

Likewise, I have shortened the conclusion, focusing on summarising the results of the research and discussing potential implications of the research.

Comment 3. This article should define research hypotheses.

Answer:

I have changed the text to make the research hypotheses more explicit. I write:

In summary, I have three I have three nested research hypothesis that I wish to test empirically.

\* Solar panels are not pure commodities. Significant quality differences can be detected between manufacturers of panels.

\* Given that quality differences exist between manufacturers, high information owners (third-party owners) will purchase higher quality panels than low-information owners (host owners).

\*Price and quality will be more highly correlated in solar panel systems owned by high information owners.

Comment 4.

The quality of the whole written text should be improved.

Answer:

I agree that the quality of the text needed improvement. I have had the article copy-edited, and have tried to carefully edit the manuscript for clarity. I have re-organized sections, especially the introduction and conclusion, to emphasize the contributions of the paper. I have also added tables explaining precisely the symbols used in the models (P.10,11 and 17)