MARKET EQUILIBRIUM STRATEGIES UNDER LEARNING BY DOING SPILLOVERS

[Franz Wirl, University of Vienna, Faculty of Business, Economics and Statistics , +43-1-4277-38101, franz.wirl@univie.ac.at]
[Markus Eigruber, Vienna University of Technology, +43-1-58801-33087, markus.eigruber@tuwien.ac.at]

Overview

The phenomenon of improving performance in any activity by simply exercising it over and over again, i.e., *learning by doing*, is known at least since Aristotle's famous lore:

"*For the things we have to learn before we can do them, we learn by doing them*."

It features prominently in production from airplanes to microchips, automobiles (Ford's Model T), and to the field of renewable energy technologies. In the latter the estimation of learning curves is a common exercise carried out in countless scientific papers as well as non-scientific industry reports. In this field, learning by doing is crucial because the major technologies are established and long known, e.g., wind turbines, the electric motor (invented sooner than the combustion engine), photovaltaics (PV) and batteries, where major eficiency improvements have been recorded from learning by doing. The average PV-module price has came down from above 100 2019-US$ per W(peak) in 1976 to around 0.2 at present, which indicates a strong effect of learning by doing. The reduction of world market prices (as a proxy of the costs of a competitive industry) is linked to cumulative production and although this linkage is common in the empirical literature, this assumption raises a few important questions:

- How to differentiate learning from autonomous technological improvement?
- How can competitive markets support learning?
- How to separate price reductions from effects other than learning?
- Do markets allow for competition in the long run, in particular if some, possibly only weak, asymmetries exist (like one firm having a head start)?

To answer these questions we investigate intertemporal strategic interactions for the whole range of industrial organizations (monopolies, cartels, oligopolies and competitive markets) in case they benefit from firm internal *as well as* external learning by doing.

Methods

An analysis of this interplay between learning from own production and from those of others combined with the interaction in the goods market requires to account for dynamics and strategic interactions. Hence, we develop a differential game of n players and n states and carry carry out the analysis for the standard power function representation of learning cost curves (panel cost has historically declined at roughly 20% for each doubling of output) and also for a linear one. The first model is non-linear, whereas the latter one is linear-quadratic. We study and compare equilibrium strategies (open-loop and feedback, where tractable), which is a computationally tough problem. All equilibria and their properties are then compared. A special emphasis is put on the question whether the outcome is indeed uniquely determined or even existing.

Results

1. The non-linear setup of the power function can lead to different long run outcomes depending on the initial conditions -- even for a monopoly. More precisely, thresholds determine whether the process of learning

will start or not. These markets are characterized by a single binary decision to start producing modules or quit the business immediately.

2. Irrespective of the specification of the learning cost function, perfect competition cannot support intertemporal knowledge accumulation.

3. To our surprise the linear-quadratic differential game features surprising properties of the linear Markov perfect equilibrium (LMPE): Multiple LMPEs can and do exist in this game. Unlike the multiple equilibria in non-linear strategies, the non-uniqueness of linear Markov perfect equilibria is mostly ignored in the literature. To this end we compare our results with the very few (two and only arithmetic) examples in the literature where multiplicity in feedback strategies have been reported. Our paper presents the first economically meaningful differential game with the above-mentioned properties.

4. Strategic intertemporal interactions lead to more output and learning compared with an equilibrium in open loop strategies.

Conclusions

We analyze intertemporal market equilibria under internal as well as external learning by doing to describe how learning affects the costs of PV-module manufacturers. The major implication of our analysis from an economic policy perspective is that the pair of competition and learning by doing does not match well. Of course, not under perfect competition, but also not for oligopolies. In particular, a LMPE exists only over a fairly restricted domain of parameters and only for few firms experiencing suffcient knowledge spillovers. In contrast, the open loop strategies allow for an oligopolistc outcome over a large domain of spillovers and for more and even for many firms. However, if a LMPE exists, then it leads to higher output (and learning) and may lead to multiple symmetric equilibria, which is a phenomenon that is by and large overlooked.

We conclude with a welfare analysis and suggest that policymakers, who anticipate the respective outcome, may need to steer such markets towards the social optimum, which could involve offering a limited amount of operating licenses.

The puzzling feature of multiple symmetric LMPEs of a LQ differential game suggests to explore the underlying economic and arithmetical reasons and conditions for such an outcome in general as well as in other models. Our study suggests that a larger state space and, presumably also, interaction in the state dynamics are necessary to obtain multiple and symmetric LMPEs. This requires further research.

(Some) References

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