Towards a dynamic model of the industrial upgrading with global value chains

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1 | INTRODUCTION

Industrial upgrading along the value chains has been widely discussed in the management and regional studies literature since the late 1990s when the whole world entered into the era of globalisation (Gereffi, 1999; Gereffi et al., 2005; Giuliani et al., 2005; Humphrey & Schmitz, 2001, 2002; Lee et al., 2020; Schmitz, 2004; and many others). The increasing level of offshore outsourcing around the globe also gives rise to the phenomenon of value chain industrial upgrading, in which suppliers in developing countries that specialise at low value-added stages can develop capabilities by entering into the high value-added stages that are normally dominated by firms in developed countries (Shen et al., 2020; Wan & Wu, 2017). Nonetheless, it is rather surprising that its formalisation, especially with reference to the micro-mechanism of industrial upgrading along the global value chains, has been very much unexplored in the economics literature.

Although theoretical works on the correlation between firms’ micro-behaviours and their value chain upgrading along the value chains are surprisingly under-developed, the empirical patterns regarding industry-level profit-sharing, cost sharing, output and pricing dynamics as well as the value-added dynamics with respect to the upstreamness of the value chains in different countries obtained from the World Input-Output Database (WIOD) lay the foundation for our theoretical model. We find more upstream industries are correlated with higher profitability and value-added. In addition, upstream industries tend to be more capital-intensive, have higher output capacity and invest more in
R&D. Average cost on the other hand exhibits a U-shaped pattern for industries with higher upstreamness. In Appendix, we discuss in detail the corresponding figure and regression result for each of the above observed empirical patterns.

Bearing these industry-level stylised facts in mind, the topic regarding the relationships among firm-level dynamics (including output, prices, cost, and profitability and upstreamness of the value chains) is surprisingly under-developed in the existing literature. Our paper is also further motivated to examine at the global level whether those industries in every country that are more integrated into the global value chain trade are also those located at the more downstream stages, which also suffer from lower value-added, profitability, capital and output. If this holds true, then it becomes crucial for firms from these downstream industries that are more integrated into the global value chain to upgrade themselves towards the more upstream positions of the chains, because by doing so they could acquire higher levels of profitability, value-added, output capacity and capital.

We use the data from WIOD and set GVC equal to 1 if industries have their Vertical Specialization Index (Wang et al., 2018) above the median value of VSI in China, indicating these industries are more integrated into the global value chain and 0 otherwise.\(^1\) Table B3 of Appendix B illustrates that after controlling for the year fixed effects, industries that are more integrated in the global value chains are more downstream and have lower levels of value-added, capital, output capacity and profit.

To the best of our knowledge, this research is the first attempt in the literature at formalising the theory of a firm’s industrial upgrading mechanism along the global value chains. Our model investigates how prices, outputs, cost structure and profitability at the firm level evolve during the firm’s industrial upgrading along the value chains. In other words, we provide a theoretical treatment of deriving the optimal trajectories regarding how prices, outputs, cost level and profits vary when firms in the value chains move from downstream to upstream stages. Therefore, what sets our paper apart from other works is illustrating the relevance of the microeconomic dynamics of firms’ behaviours during industrial upgrading along value chains.

The model in this paper is inspired by the pioneering work of Costinot et al. (2013). In their sequential production model, they treated the production pattern of global value chains as the sequential process, and firms producing at each perfectly competitive stage are subject to certain mistakes that depend upon the level of firms’ total factor productivity. Different from Costinot et al. (2013)’s multi-country model setting, our multi-firm sequential production model incorporates the classical continuous time optimisation problem into the sequential production framework, and we study the micro-mechanism of industrial upgrading along the value chains. Our model treats the mistake rate of production as an endogenous parameter that is determined by the level of sunk cost, including R&D expenditure and any other costs related to quality or technology upgrading activities. Such endogenous treatment of the mistake rate of production along the value chains allows us to detect the channel through which firms can succeed at upgrading from downstream to upstream stages by acquiring higher profitability via investing more money on quality or technology upgrading activities, which is crucial for our understanding of industry upgrading dynamics.

According to our model, we offer the following contributions to the existing literature regarding firms’ pricing and output setting strategies along the value chains. (a) In terms of firms’ pricing decisions, once they go from downstream stages to relatively upstream stages, the price level of intermediate goods moves correspondingly lower. This makes sense, because the price level of intermediate goods provided by the more upstream firms must be lower than the price level set by those upstream firms closer to the final goods consumers; otherwise, no firms in the value chains could make viable profits. (b) We also show when firms move from downstream to upstream stages that their output level

\(^1\)The median of VSI for all countries is similar to that of China.
increases with the upstreamness of the value chains if and only if the decreasing rate of change of input demand with respect to the price set by firms at the production stage is not sufficiently high. The intuition behind this is that if industrial upgrading along the value chains is a process by which firms move from low value-added stages to high value-added ones with escalating expenditure on R&D and other quality or technological upgrading activities, then the output capacity of the more upstream firms expands as a result of such continuous innovation process.

Our theoretical findings on output dynamics along the value chains are consistent with other works in the innovation economics literature, which state that there is a positive relationship between output and firms’ expenditure on R&D (Chen & Lee, 2020; Cohen et al., 1987; Keng et al., 2020; Shefer & Frenkel, 2005). However, our model also shows that the premise of maintaining such a high level of output capacity is to ensure that firms moving towards relatively more upstream stages should not set too high a price level of intermediate goods, because this would shrink their input demand from their vertically linked downstream buyers. The rationale behind this condition is that if the intermediate price level set by upstream suppliers is too high, then the downstream buyers respond by restricting their input demand, which would cause a decline in the output capacity of upstream input suppliers.

Another big theoretical contribution that the present paper makes is that we demonstrate that a dynamic optimisation model illustrates the relevance of the cost and profitability dynamics along the global value chains via its relations to the industrial upgrading process of firms. With respect to the optimal total cost path along the value chains, we show that the cost level is lower when firms climb from downstream stages to relatively more upstream stages in the value chains if and only if the decreasing rate of change of input demand with respect to the price set by firms at a production stage is sufficiently large. The intuition behind this is that, first, when firms climb from downstream to relatively more upstream stages, they incur a higher level of sunk cost that pushes up their overall cost level. Second, as shown in the model, when firms move to more upstream stages, they also encounter the problems of a higher mistake rate of production, which would also more likely push firms’ cost higher.

The overall cost level might also decrease if firms move towards more upstream stages when their vertically linked downstream buyers shrink their input demand more disproportionately by responding to the higher input prices set by the upstream suppliers. The logic behind this is that although firms moving towards more upstream stages might expend more money into sunk costs (including R&D expenditure), it would result in higher intermediate input prices charged by these firms. However, such an intermediate input price effect might be mitigated by the input demand shrinkage effect if downstream buyers decrease their input demand much more disproportionately than the rise in input prices. As a result, the output shrinkage effect might lead to a large decline in upstream suppliers’ output capacity, which ultimately leads to a lower cost when firms move from downstream to relatively more upstream stages.

In terms of the profitability dynamics, our model shows that firms in the value chains are capable of upgrading from downstream to upstream stages by acquiring higher profitability if and only if the following three conditions are satisfied. First, the increasing rate of sunk cost (including R&D expenditure) over sequential stages of production cannot be sufficiently large. Second, the decreasing rate of change of input demand with respect to the price set by firms at the production stage cannot be sufficiently high. Third, the decreasing rate of change of input demand with respect to the pricing dynamics over the sequential stages of production cannot be sufficiently large.

The theoretical results on the variation of profitability with respect to the upstreamness of production stages shed important light on the key factors that could drive the success of the industrial upgrading process for firms producing along the value chains. First of all, it is known that when firms move from downstream to relatively upstream stages, it is inevitable that they must incur higher sunk
costs. Therefore, if the increasing rate of change of sunk costs (including R&D expenditure) with respect to the upstreamness of value chains becomes too large, then it is very likely firms moving towards upstream stages might incur losses. Second, when firms want to upgrade from downstream to more upstream stages, they should not set too high input prices, because by doing so their downstream buyers will respond to the higher input prices by largely reducing their input demand. The reduction in the input demand results in a lower level of output capacity from these firms, which could mitigate the increasing rate of profits during the upgrading process. Moreover, the increasing rate of profits with respect to the upstreamness of value chains could be also undermined if the pricing dynamics over the sequential stages of production become more uncertain and unstable. In other words, as suggested by our model, if the rate of change of input prices with respect to the upstreamness of the value chains becomes more volatile, then firms moving towards upstream stages will respond to the higher volatility of input prices dynamics by restricting their output capacity. In this case, the output shrinkage effect could make it possible for upgrading firms to not be able to capture higher profitability.

The rest of the paper runs as follows. Section 2 is the relevant literature review. Section 3 is the theoretical model. Section 4 is discussions on the relevant policy implications of our theoretical model with respect to China’s industrial development. The final section is the conclusion.

2 | LITERATURE REVIEW

This research stands at the intersection of two streams of the literature. One covers value chain upgrading in the management and regional studies literature, and the other one is quality upgrading in the international trade literature. In terms of the management and regional studies literature, several papers related to our work are worth mentioning. The first piece of work is by Gereffi (1999), who used the apparel industry with emphasis on Asia as a case study to examine the industrial upgrading trajectories from assembly to OEM and to OBM export roles. However, he did not explore the micro-economic dynamics of the industrial upgrading from OEM to OBM along the value chains such as the cost structure change or profitability level change through the process of upgrading. Our paper fills this gap and unlocks the micro-foundation of industrial upgrading along the chains.

Gereffi et al. (2005) next analysed the value chain industrial upgrading from the governance perspective. They argued that there are three key variables that determine how industrial upgrading along the value chains is governed: (a) the complexity of the transaction; (b) the ability to codify the transaction; and (c) the capabilities in the supply base. Our paper takes one step further to formalise the concepts of these three key variables and unifies them into an analytical framework. For instance, the introduction of the mistake rate that is endogenous to the level of sunk cost (mainly including R&D expenditure in our model) enables us to formalise the idea that firms present more intensive R&D under higher complexity of production when they move from downstream to upstream stages that naturally have more intensive R&D and high value-added.

Second, the ability to codify a transaction is also modelled by using the concept of sunk cost in our model. The model presumes that the sunk cost (include the R&D expenditure and other quality-upgrading related cost) along the value chains positively varies with the upstreamness of the value chains. Therefore, firms upgrading towards relatively more upstream stages are more likely to possess a greater ability to codify the transaction, because in the upstream stages their R&D and human capital are very intensive.

Third, the capabilities in the supply base of firms producing along the value chains are formalised by the output dynamics in the model. Firms specialising at relatively more upstream stages mainly include R&D-intensive and capital-intensive sectors, which have higher capabilities in the supply
base. This is because, as argued previously, the higher innovation capabilities will enable the upstream firms to obtain higher growth prospects, thus leading to higher output levels. Moreover, higher output levels of firms at the upstream stages generate more opportunities for them to outsource some non-core operations to other sub-contractors, thus further increasing the capabilities of these firms’ supply base.²

Humphrey and Schmitz (2001) illustrated the relevance of how the risk of supplier failure induces some firms from emerging markets to become the new global lead buyers in the value chains. In line with the spirit of his paper, we introduce 4 main elements in our model regarding the prices that firms must pay during the industrial upgrading process. First, the introduction of the mistake rate in our model is an indirect measure of supplier failure within the value chains. We argue that the mistake rate along the value chain increases with respect to the upstreamness of the value chains. This means firms in relatively more upstream stages are subject to higher mistake rates and vice versa for the relatively more downstream stages. This makes sense, because many upstream R&D-intensive firms are subject to higher risks of product invention failure. Second, from the cost–benefit analysis perspective, a higher mistake rate during the production process for upstream firms also implies that when firms upgrade from downstream to more upstream stages, they inevitably bear a higher level of cost burden, which also raises the risks of production failure. Third, the other downside that might stem from firms’ industrial upgrading process along the value chains is that they might charge too high input prices, which could largely constrain their output capacity due to shrinkage of input demand from downstream buyers. This means if downstream buyers respond to the higher input prices charged by upstream suppliers by greatly cutting their input demand, then those firms upgrading towards upstream stages might incur losses. Fourth, firms producing along the value chains may fail to upgrade if they encounter higher volatility of prices over the sequential stages of production, because if upstream firms expect that there will be a higher level of uncertainty in price changes that might be potentially caused by an external policy shock (like oil prices) or other institutional factors, then they might respond by restricting their output expansion, which could again lead to losses during their upgrading process.

Schmitz (2004) argued that low labour costs alone do not sufficiently explain the transformation of some industries within developing countries. He instead contended the view that global value chain analysis, with its emphasis on the coordination of seemingly fragmented production sites, helps to explain the global reallocation in manufacturing. Accordingly, there are three reasons pushing the firms along the value chains to upgrade. (a) The growth in production capability is greater than the growth in demand, leading to pressure of price declines. (b) Global buyers that have facilitated the spread of production capability keep scouting for low-wage suppliers, dragging the established producers into a race to the bottom. (c) The dispersal of production capabilities is not accompanied by a dispersal of innovation activities.

What sets the model in our paper apart from his work is that we further formalise these three causes for firms to upgrade and put them into an analytical framework. First, from our model, the higher production capabilities in upstream industries are accompanied by lower price levels the firms could charge, thus corroborating the first point that he mentioned in this paper. Second, most upstream companies in the value chains are high value-added and R&D-intensive firms, indicating that they could have large production capabilities for supply base sharing via outsourcing their non-core operations to downstream sub-contractors. It could be argued that these sub-contractors are normally downstream manufacturers that employ low-wage workers, and at the same time they also face higher intensity of

²Tung and Wan (2013, 2014) illustrated similar views on how some firms concentrating on upstream stages in the value chains such as Apple and HP could have higher supply base capabilities by sharing common sub-contractors like Foxconn.
external competition from their counterparts. Third, our model shows that only when firms move from downstream to upstream stages do they engage in innovation activities more frequently, because they must spend more expenditure on R&D and any other quality-related upgrading activities. However, for those firms producing at the downstream low value-added stages, it is obvious that they are not committed to R&D activities. Hence, our theoretical findings are consistent with the third factor for firms to upgrade that has been proposed by Schmitz (2004).

The second stream of research that closely correlates to our work is quality upgrading in the international trade literature. The paper by Sutton (2012) regarding the concept of revealed capabilities is worth mentioning. According to Sutton (2012), a supplier's achievement of each milestone reveals the intermediate level of capabilities that the supplier developed up to that point. In line with his argument, our model shows that profits, pricing, output and cost dynamics all align with the nature of sequential production—that is, some firms want to achieve a certain level of profitability up to a certain level at some upstream stages, and then they must accumulate profits at a lower level in the downstream stages. Sutton's concept of firms' capability building is thus similar to the idea of industrial upgrading along the value chains in our paper.

Wan and Wu (2017) built an analytical model to study the impact of value chain climbing on value distribution in vertical relationships, finding that success in value chain climbing depends on the relative competitiveness in the product market and the supplier's speed of capability development. Our paper differs from their work in two aspects. First, despite the fact that they explored the capability dynamics during the process of value chain climbing, they did not give a formal analytical description of what is the micro-level foundation of capability. In our work, we equalise the concept of capability to the profitability as well as the output level of firms along the chains, which can help better model the firms’ behaviour. Second, in their paper the downside of value chain upgrading is that the incumbents in the high value-added stages might deter the entry of suppliers and squeeze out new entrants. In contrast to their framework, we model the downside of industrial upgrading by using the concept of the mistake rate along the value chains that is endogenous to the level of sunk cost that firms must incur during the industrial upgrading process. We argue that as firms move towards the high value-added upstream stages, they will spend more money on R&D and other similar quality or technology-related upgrading activities that are usually endowed with higher risk of production failure. Second, we further introduce another two mechanisms through which firms might fail to upgrade. One is that when firms move towards more upstream stages, if they charge too high input prices, then their downstream buyers could reduce their input demand, which could result into a reduction of these firms’ output capacity. The other one is that the output capacity of firms moving towards upstream stages could be negatively affected by the uncertainty arising from the pricing dynamics over the sequential stages of production.

Another paper by Verhoogen (2008) proposed a new mechanism linking trade and wage inequality in developing countries, which is the quality-upgrading mechanism. He found that more productive plants produce higher-quality goods than less productive plants, and they pay higher wages in order to maintain a high-quality workforce. His findings on the positive correlation between higher productivity and higher-quality workforce are consistent with our proposed upgrading channels through which more profitable upstream firms with higher levels of total factor productivity caused by more R&D input are also able to possess higher output capacity. This is mainly because firms in the upstream stages are normally in R&D- or knowledge-intensive stages, which require high-quality workforce. However, what sets our work apart from his paper is that he did not incorporate quality upgrading in the context of sequential production, which our paper does.

Using empirical data from Brazilian exporters, Flach (2016) came up with a point that due to quality-based market segmentation, firms raise quality and prices to high-income destinations in order
to adapt to the destination country’s characteristics. His theories are compatible with the views in our paper, whereby the profitability level is higher once firms upgrade along the value chains from downstream to upstream stages, which are normally dominated by firms from high-income countries. However, the difference between our paper and his is that we incorporate such quality and pricing upgrading under the context of sequential production, whereas he only considered it as the standard exporting problem.

What sets this paper apart from the existing literature is that we offer the first attempt to model the micro-behaviours of firms including their pricing and output strategy as well as cost and profitability dynamics along the value chains. The previous literature either has focused on the macro-level developmental implications of the value chains on a country's welfare dynamics or how participation in the value chains affects the global income distribution. Scant works have touched upon the firm-level behaviour along the value chains. This is where we begin.

3 | MODEL

3.1 | Basic environment

Our model is inspired by the classical continuous time optimisation model in which one wants to seek an optimal trajectory that maximises or minimises a given integral expression. This integral expression is a function of the independent variable $t$, the function that we are interested in $x(t)$, and its derivative $\dot{x}$. Ever since the pioneering work by Costinot et al. (2013), it is widely accepted in the international trade literature that the production pattern within the global supply chains can be regarded as a continuous process in which the production stages are sequential, and the firm must produce sequentially along the production stages in the supply chains and be subject to certain mistakes rate that vary across different stages along the chains. From this perspective, the sequential nature of the production pattern along the supply chains enables us to use the similar dynamic optimisation problem to study the issues of industrial upgrading at the firm level.

In line with the spirit of Costinot et al. (2013), it is assumed that the production of the final good is sequential. To produce the final good, a continuum of stages $s \in S = (0, S)$ must be performed. When $s = 0$, the stage is the most downstream, whereas when $s = S$, the stage is the most upstream. At each stage, producing one unit of intermediate good requires one unit of the intermediate good produced in the previous stage. Such a setting implies that “intermediate good $S$” is in infinite supply and has a price equal to $p_S$. “Intermediate good 0” corresponds to the final unique good, for which its world price is equal to $p_0$, indicating that $p(0) = p_0$.

Suppose that the market structure of each production stage is perfectly competitive, and therefore, the price of the intermediate good at a given production stage in the chains is also exogenous, which is given by $p(s)$. Likewise, in terms of the output dynamics along the global supply chains, it is assumed that the number of units a representative firm at each production stage in the chain sells depends on both the price of the intermediate good at that stage $p(s)$ and the rate of change of price $p'(s)$. The rationale behind this is that how much output the firm at each stage will decide to produce is not only determined by the price level that it is willing to charge, but also depends upon the price level that its upstream firm is willing to sell the inputs by and the price level at which its downstream firm is willing to buy, thus forming the dynamic change in the price level over the sequential stages of production.

The functional form of output dynamics can thus be characterised as follows:

\[ q(s) = a p(s) + b p'(s) + q_0, \]
where \( a < 0 \) indicates that the higher level of price that a representative firm is willing to charge, the lower level of output that it is willing to produce as its vertically linked downstream firm will buy a lower amount of inputs due to the higher input prices. In other words, variable \( a \) measures the decreasing rate in the change of intermediate input demand from downstream buyers with respect to the price level set by the upstream suppliers at a production stage. We denote it as the intermediate input price effect. Moreover, \( b < 0 \) implies that if the rate of change of price over the sequential stages of production is higher, then the firm at each stage faces a higher level of uncertainty in the final price that is determined between this firm and its vertically linked firms, which could result in a lower level of output capacity of firms producing along the value chains. Parameter \( b \) could be the indirect proxy of how each firm shrinks its production when there is a higher level of pricing volatility along the supply chains mainly stemming from an external policy shock or institutional factors. For instance, if there is an oil price shock around the globe, then we expect parameter \( b \) to be sufficiently negative. Thus, we denote \( b \) to be the measure of sequential price uncertainty effect. Finally, \( q_0 \) is the output level produced by a representative firm that is not contingent upon where this firm locates at in the chains.

Motivated by the stylised facts indicated by the U-shape cost sharing pattern along the value chains that have been discussed in the introduction section, it is assumed that the production cost function \( z(s) \) with respect to the stages of production shows the following cubic form:

\[
z(s) = m[q(s)]^3 + n[q(s)]^2 + \lambda(F) + c,
\]

where \( m > 0 \) indicates that the long-run average cost dynamics exhibit a U-shape pattern, which is in line with the standard microeconomic theory. Here, \( n < 0 \) means that the minimum level of production cost of firms specialising at the midstream stage of the value chains cannot be negative. Moreover, \( c \) is the production cost that is not related to the production stages, and \( c > 0 \).

Like the setting by Costinot et al. (2013), suppose that mistakes occur along the global supply chains at a constant Poisson rate, which can be denoted as \( \lambda \) and \( \lambda \geq 1 \). A higher value of \( \lambda \) means a higher level of production cost that a firm at stage \( s \) must incur and a higher possibility that firms in the value chains might encounter production failure. Term \( \lambda \) is also an endogenous parameter determined by the amount of sunk cost that the firm at a production stage spends on R&D or any other quality-upgrading-related activities.

It is assumed \( \lambda = (F(s))^2 \), implying that if the firm at a production stage spends a higher level of sunk cost (mainly including R&D cost), then it will face a higher level of a mistake rate. This makes sense, because it is common that there will be higher risks and uncertainty arising from the process of product innovation or design compared with those low value-added activities undertaken by firms mainly specialising in manufacturing or assembly production stages in the value chains. As a result, this results in a higher possibility for firms to encounter more severe problems of output destruction—that is, higher mistakes during production.

Consistent with the stylised facts presented in the introduction section, the functional form of sunk cost that firms in the value chains must incur is also assumed to positively correlate with the upstreamness of the value chains, which can be expressed as the following linear form \( F = ks \) where \( k > 0 \). This function form for the sunk cost indicates that the sunk cost level in our model is endogenously determined by the upstreamness of value chains, meaning that when firms move from downstream to more upstream stages, they will incur a higher sunk cost. Here, \( k \) thus measures the endogenous sunk cost effect of firms’ upgrading mechanism along global supply chains. This is reasonable, because as shown in the introductory section, most upstream industries exhibit a high level of capital-intensive-ness and R&D-intensiveness, such as heavy industries, telecommunications, high-tech sectors and so
on. Therefore, if firms from downstream stages move towards upstream stages in the value chains, then it is natural to see that they will incur a higher level of sunk cost.

It is worth noting here that our setting on the sunk cost is also in line with the spirit of the endogenous sunk framework developed by Sutton (1991), but from a slightly different approach. The common point between our model and Sutton’s is that we both make the sunk cost endogenous. Nevertheless, the main difference lies in the fact that the sunk cost is endogenous to the level of quality of goods provided by firms in Sutton’s framework, while the sunk cost in our model is endogenously determined by the upstreamness of the value chains. Bearing that in mind, we re-write the production cost dynamics of firms producing along the value chains as follows:

\[ z(s) = m[q(s)]^3 + n[q(s)]^2 + k^2s^2 + c \]  \hspace{1cm} (3)

### 3.2 Solution

Taking everything into account, we express the dynamic optimisation problem faced by a representative firm regarding the optimal pricing dynamics over \(0 \leq s \leq S\) at a production stage in the value chain as follows:

\[
\text{Max} \int_0^S [p(s)q(s) - z(s)] \, ds \tag{4}
\]

Subject to:

\[ p(0) = p_0, \quad p(S) = p_s \tag{5} \]

Here, \(z(s) = m[q(s)]^3 + n[q(s)]^2 + k^2s^2 + c\), \(\dot{p}(s) = \frac{1}{b} [q(s) - ap(s) - q_0]\). The dynamic optimisation problem indicated by (4) and (5) is an optimal control problem in continuous time in a deterministic environment, where \(p(s)\) is a state variable and \(q(s)\) is a control variable.

Plugging \(z(s)\) and \(\dot{p}(s)\) into (4), we further express the dynamic optimisation problem as follows:

\[
\text{Max} V(s) = \text{Max} \int_0^S \left\{ p(s)q(s) - m[q(s)]^3 - n[q(s)]^2 + k^2s^2 - c \right\} \, ds \tag{6}
\]

From (6), we define the following Hamiltonian function:

\[
\mathcal{H}(t, p(s), q(s), \lambda(s)) = p(s)q(s) - z(s) + \lambda(s) \dot{p}(s)
\]

\[
= p(s)q(s) - m[q(s)]^3 - n[q(s)]^2 + k^2s^2 - c + \lambda(s) \frac{1}{b} [q(s) - ap(s) - q_0] \tag{7}
\]

From (7), we know that three necessary conditions for this Hamiltonian function are:

\[
\begin{cases} 
\frac{\partial H}{\partial q} = p(s) - 3m[q(s)]^2 - 2nq(s) + \lambda(s) \frac{1}{b} = 0 \\
\frac{\partial H}{\partial p} = -[q(s) - a\lambda(s)] = -q(s) + a\lambda(s) \\
\dot{p}(s) = \frac{1}{b} [q(s) - ap(s) - q_0] 
\end{cases} \quad \tag{8}
\]
From (8), we rearrange these three necessary conditions as follows:

\[
\begin{align*}
\dot{q}(s) &= -\frac{a}{b} p(s) - \frac{a}{b} \lambda(s) + \frac{a}{b} q(s) - \frac{6mq(s) + 2n}{b} u_1(s)
\end{align*}
\]

\[
\dot{p}(s) = \frac{1}{b} \left[ q(s) - ap(s) - q_0 \right]
\]

Since Equation (9) is a system of non-linear differential equation, it is hard to obtain closed-form solutions for the optimal trajectory of prices, output, profits and cost dynamics over the sequential stages of production. Hence, simulation techniques are used here to solve for the optimal path for the prices, output, profits and cost dynamics when firms move from downstream to relatively more upstream stages. For the baseline model of the simulation, we first calibrate some of the parameters as follows: \( q_0 = 100; p_0 = 100; \lambda_0 = -1; c = 1; m = 0.0001; n = -0.0001; a = -0.001; b = -100; \) and \( k = 1. \) The system of differential equations indicated by (9) can be written as:

\[
\begin{align*}
\dot{q}(s) &= -0.00001p(s) + 1 + 0.00001\lambda(s) \\
\dot{\lambda}(s) &= -q(s) - 0.0002 \left( \frac{q(s) - 0.01q(s) - 0.00001p(s) + 1}{b} \right)
\end{align*}
\]

From Equation (10), we, respectively, simulate the optimal trajectory for prices, output, profits and cost dynamics when firms move from downstream to upstream stages in the value chains (Figure 1).

From Figure 1, we derive the first proposition in this paper.

**Proposition 1** With the parameterisation of \( q_0 = 100; p_0 = 100; \lambda_0 = -1; c = 1; m = 0.0001; n = -0.0001; a = -0.001; b = -100; \) and \( k = 1, \) when firms move from downstream to relatively upstream stages, the following four optimal trajectories are documented. (a) The intermediate input prices decrease with the upstreamness of the value chains. (b) The output increases with the upstreamness of the value chains. (c) The total cost increases with the upstreamness of the value chains. (d) The profits increase with the upstreamness of the value chains.

Proposition 1 implies that when firms climb from downstream to upstream stages, the price levels of the inputs they could charge become smaller. This makes sense for two reasons. First, when firms move towards upstream stages where the production of goods becomes more distant from final good consumers, the price level of more upstream intermediate inputs must be lower than that of the downstream inputs. Second, when firms move towards more upstream stages, they cannot charge too high prices, because by doing so this largely reduces the input demand from their downstream vertically linked input buyers. It could be also seen that output will be higher when firms climb from downstream to more upstream stages. The rationale behind this is that firms specialising in the more upstream stage must spend more money on R&D expenditure and other quality-upgrading-related sunk costs; thus, they are more likely to generate higher output capacity that allows them to produce at the upstream stages. Moreover, the total cost level will increase over the upstreamness of the value chains, denoting that when firms move from downstream towards more upstream stages, in order to successfully upgrade via acquiring higher profitability, they must incur more R&D expenditure and any other quality-upgrading related sunk cost, thus leading to a higher cost level for firms during the
industrial upgrading process along the value chains. The above figure also shows firms’ profitability positively varies with the upstreamness of the value chains, implying that moving towards upstream stages enables them to upgrade and have higher capabilities. This is reasonable, because firms that are more R&D-intensive and capital-intensive, by specialising in the more upstream stages with high value-added, are more capable of capturing higher profitability.

### 3.3 Comparative statics

This section conducts comparative statics analysis to detect the channel through which the optimal trajectory of intermediate input prices, output, costs and profitability might vary with different parameters in the model. In other words, it might be interesting to explore under what condition Proposition 1 does not hold when several parameters in the model such as $k$, $a$ and $b$ vary. First, we look at how the variation in parameter $k$ (i.e., changes in the magnitude of the increasing rate of change of sunk cost with respect to the upstreamness of the value chains) affects the optimal paths of prices, output, costs and profitability during firms’ value chain upgrading process. The following Figure 2 shows the comparative statics analysis in terms of the parameter $k$.

From Figure 2, we derive the second proposition in this paper.

**Proposition 2**  
*Endogenous Sunk Cost Effect* When the magnitude of the increasing rate of sunk cost that firms must spend with respect to the upstreamness of the value chains ($k$) becomes
sufficiently large, the optimal trajectories of intermediate input prices, output, total cost and profitability of firms when they move from downstream to upstream stages are documented as follows. (a) The intermediate input prices decrease as firms move from downstream to upstream stages. (b) The output level increases as firms move from downstream to upstream stages. (c) The cost level increases more sharply when firms move from downstream to upstream stages. (d) The profitability level decreases when firms move from downstream to upstream stages.

Proposition 2 indicates that when firms move from downstream stages to upstream stages in the value chains, if the magnitude of the increasing rate of the sunk cost (mainly including R&D expenditure) and any other quality-upgrading-related costs with respect to the degree of upstreamness of the value chains become larger, then there will be no impact on firms’ optimal output and pricing strategy. However, the story is different for the cost and profit dynamics for those firms climbing towards more upstream stages along the value chains. Here, the total cost level for firms will increase more sharply when they move towards more upstream stages, which makes sense, because if the degree to which upgrading firms spend on the R&D expenditure or any other quality-upgrading sunk cost becomes too high, then this raises the overall cost level of those upgrading firms in a much quicker way. Indeed, from the above figure when $k = 30$, the cost level of firms increases most sharply with respect to the upstreamness of the value chains compared with the case when $k = 1, 10, 20$ and $25$. 

**FIGURE 2** The comparative statics of $k$. Notes: The results are simulated by SciPy, a Python-based ecosystem of open-source software for mathematics, science and engineering, with parameter values: $q_0 = 100; p_0 = 100; \lambda_0 = -1; c = 1; m = 0.0001; n = -0.0001; a = -0.001; \text{and} b = 100$.
It becomes more interesting if we look at how the optimal trajectory of profitability changes when there is a rise in the magnitude of the increasing rate of the sunk cost (mainly including R&D expenditure) with respect to the degree of upstreamness of the value chains. The above figure shows that when $k$ becomes sufficiently large (that is, $k = 30$), the profitability will become lower when firms move towards more upstream stages. This makes sense, because when firms spend too much on a sunk cost like R&D expenditure, it may offset the benefits that they could capture during the upgrading process and lead to a lower rate of profit increase obtained by these upgrading firms. It should be argued that when firms attempt to upgrade along the value chains, they have to pay the price with particular reference to the escalating level of sunk cost arising from more R&D-intensive activities, which are normally featured by a higher risk of production failure (higher mistake rate). We denote the phenomenon of lower profitability of upgrading firms brought by the escalating sunk cost as the endogenous sunk cost effect of firms’ upgrading process along the global value chains.

We next look at the comparative static analysis of parameter $a$, which is the decreasing rate in the change of intermediate input demand from downstream buyers with respect to the price level set by the upstream suppliers. When the decreasing rate of the intermediate input demand from downstream buyers with respect to the price set by its upstream suppliers at a production stage becomes more negative, we can simulate the corresponding comparative static analysis in terms of the optimal trajectories of output, prices, total cost level and profitability of firms climbing along the value chains. The simulation results are presented as Figure 3.

From Figure 3, we derive the third proposition in this paper.

**Proposition 3** Intermediate Input Price Effect When the magnitude of the decreasing rate of the intermediate input demand from downstream buyers with respect to the price set by upstream suppliers at a production stage ($a$) becomes sufficiently negative, the optimal trajectories of intermediate input prices, output, total cost and profitability of firms when they move from downstream to upstream stages are documented as follows. (a) The intermediate input prices decrease as firms move from downstream to upstream stages. (b) The output level decreases as firms move from downstream to upstream stages. (c) The cost level decreases when firms move from downstream to upstream stages. (d) The profitability level decreases when firms move from downstream to upstream stages.

From Figure 3, we see that once the decreasing rate of the intermediate input demand from downstream buyers with respect to the price set by upstream suppliers at a production stage becomes more negative, the downstream buyers will become more sensitive and responsive to the price set by those upstream suppliers. Moreover, the price set by firms moving towards more upstream stages will decrease more sharply to a larger degree, because these upgrading firms are not willing to charge too high prices in order to prevent their downstream buyers from restricting too much of their intermediate input demand. Moreover, $a$ becoming sufficiently negative ($a = -1$) means that a one unit increase in the price charged by the firms at a particular stage will lead to a one unit decrease in the intermediate input demand by their downstream buyers, and the output capacity of these upgrading firms will also begin to shrink. This makes sense, because the shrinkage of intermediate input demand induces a corresponding decline in the output capacity of upgrading firms. However, once the upgrading firms are no longer willing to charge high prices when they move from downstream stages to upstream stages, they will also incur a lower overall cost level. This is reasonable, because once the unit price of upgrading firms becomes lower, these firms must lower their unit cost to ensure that they can still earn positive profits. Moreover, since the output capacity of the upgrading firms shrinks, the overall cost level (which is the product between the decreasing level of unit cost and the shrinking level of output) will also go lower once firms move towards more upstream stages.
From Figure 3, we similarly observe that the profitability level with respect to the upstreamness of the value chains also begins to decrease when $a$ becomes sufficiently negative. This is what we call the intermediate input price effect of firms’ value chain upgrading process. This effect refers to the idea that if the downstream buyers become highly responsive to the upgrading firms’ charging of higher prices, then firms moving towards more upstream stages will incur lower profitability. This is because once the downstream buyers restrict their intermediate input demand more sharply in response to the higher prices charged by upgrading firms, then the total revenue captured by these upgrading firms will decrease to a large degree for the following two reasons. First, the output capacity will largely shrink. Second, the above figure shows that once $a$ becomes more and more negative, although cost level and price both decrease, the latter appears to decrease much more sharply than the former. As a result, the unit profit margin drops, which could result in ultimate profit losses by firms upgrading towards more upstream stages.

We further examine the comparative static analysis of parameter $b$ (Figure 4), which is the decreasing rate of change of intermediate input demand with respect to the pricing dynamics over the sequential stages of production. The simulation results are presented below regarding how the optimal trajectory of output, prices, total cost level and profitability might change when the magnitude of the decreasing rate of change of input demand varies with respect to the pricing dynamics over the sequential stages of production.

**FIGURE 3** The comparative statics of $a$. Notes: The results are simulated by SciPy, a Python-based ecosystem of open-source software for mathematics, science and engineering, with parameter values: $q_0 = 100; p_0 = 100; \lambda_0 = -1; c = 1; m = 0.0001; n = -0.0001; b = -100; and k = 1$
Proposition 4 Sequential Pricing Uncertainty Effect
When the magnitude of the decreasing rate of pricing dynamics with respect to the upstreamness of the value chains (b) becomes sufficiently negative, the optimal trajectories of intermediate input prices, output, total cost and profitability of firms when they move from downstream to upstream stages are documented as follows. (a) The intermediate input prices decrease less sharply as firms move from downstream to upstream stages. (b) The increasing rate of output level decreases as firms move from downstream to upstream stages. (c) The cost level increases less sharply when firms move from downstream to upstream stages. (d) The profitability level increases less sharply when firms move from downstream to upstream stages.

From Figure 4, we note that once parameter b becomes sufficiently negative, the decreasing rate of pricing dynamics with respect to the upstreamness of the value chains becomes much smaller. This means that if the downstream buyers are more sensitive (cutting their intermediate input demand more sharply) to the rate of changes in the prices charged by upgrading firms climbing along the value chains, then upgrading firms are not willing to further reduce their unit price more sharply, because by doing so they might run the risk of incurring disproportionate losses arising from both output capacity shrinkage from insufficient levels of intermediate input demand and too low profit margins.

**FIGURE 4** The comparative statics of $b$. Notes: The results are simulated by SciPy, a Python-based ecosystem of open-source software for mathematics, science and engineering, with parameter values: $q_0 = 100; p_0 = 100; \lambda_0 = -1; c = 1; m = 0.0001; n = -0.0001; a = -0.001$; and $k = 1$.
caused by lower unit price levels. On the other hand, from the above figure, we see that once parameter $b$ becomes sufficiently large, the increasing rate of output with respect to the upstreamness of the value chains becomes smaller. This is because once the downstream buyers respond more negatively by shrinking their intermediate input demand due to the higher volatility of pricing dynamics over the sequential stages of production, then it becomes obvious the upgrading firms will inevitably reduce their output capacity due to the shrinkage of intermediate input demand from downstream buyers.

If we look at the dynamics of cost level with respect to the upstreamness of the value chains, then the increasing rate of this overall cost level will become smaller if parameter $b$ becomes sufficiently negative ($b = -100$). The rationale behind this is because if the output capacity shrinks as a result of the higher decreasing rate of the intermediate input demand in response to the higher volatility of pricing dynamics over the value chains, then it is very likely that upgrading firms will also decrease their R&D expenditure, which means a lower level of sunk cost. More importantly, once parameter $b$ becomes sufficiently negative ($b = -100$), the increasing rate of profitability of upgrading firms with respect to the upstreamness of the value chains will be also lower, which we denote as the *sequential pricing uncertainty effect* and refers to the situation under which if intermediate input demand drops more sharply in response to the higher uncertainty (volatility) of pricing dynamics with respect to the upstreamness of the value chains, then the consequential lower level of output capacity and the less amount of input on R&D expenditure and any other quality-upgrading activities push the increasing rate of profitability during firms’ upgrading process to be lower than the case when there is lower uncertainty of sequential pricing dynamics over the value chains.

### 4 SUGGESTIVE EMPIRICAL PATTERNS AND POLICY IMPLICATIONS

#### 4.1 Some suggestive empirical patterns on the industry dynamics of China's domestic value chains

This section explores some industrial development patterns of China's economy in relation to its own value chain dynamics to further examine the validity of the theories proposed by this paper. In Figure 5, using industry-level data from WIOD, we look at how capital, R&D, output, profit and value-added vary with the upstreamness of the domestic value chains in China.

Figure 5 shows that upstream industries in China have higher levels of capital, invest more in R&D and have higher levels of output capacity, profitability and value-added. These empirical patterns in China are consistent with the theoretical results derived in this paper.

#### 4.2 Some policy discussions of domestic value chain dynamics with reference to China's industrial development

Given that the empirical patterns of the industry dynamics (including profitability, value-added, output and R&D expenditure) are in line with the theories proposed in this paper, this section discusses some policy implications of our theories in relation to the industrial development strategies of China's economy. As argued in the previous section, the more upstream industries are endowed with higher levels of value-added, profitability, capital and R&D expenditure. In terms of the adoption of an optimal global value chain upgrading strategy for China, it is of crucial importance for domestic industries that are more integrated into the global value chains to climb towards more upstream industries that
have higher profitability, value-added and capital levels. To examine the potential strategies of global value chain industrial upgrading that could be adopted by China, it is interesting to first see what type of industries in China and around the globe is more integrated into the global value chains. Using data from WIOD, we present the following summary statistics showing that the industries in China that are more integrated into the global value chains are also those domestic downstream industries.

FIGURE 5  Capital, R&D, output, profit, value-added and the upstreamness of the domestic value chains in China. Note: Measured in millions of China’s currency for capital (nominal terms)

3 The other reason why it is crucial for Chinese industries to climb up the global value chains is because it forces them to spend more money on R&D, which benefits the enhancement of their innovation capabilities.

4 For a list of Chinese industries that are more (less) integrated into global value chains in the years of 2002 and 2000, please see Appendix A at the end of this paper.
Table 1 shows those domestic industries in China that are more integrated into the global value chains are also downstream industries, because the mean value of the upstreamness for those that are more integrated in the global value chain is below 2.5 China's downstream industries that have been more integrated into global value chains exhibit lower value-added, profitability, output capacity and capital-intensiveness; as shown in Figure 5, this has become one of the main reasons causing China's economy to persistently stagnate in a circular pattern of labour-intensive and low value-added economic growth (Lu et al., 2020).

Taking the above fact into account, we offer three possible value chain upgrading industrial development strategies that could be adopted by China's domestic downstream firms as well as by China's industrial policymakers. (a) Firms from China's downstream industries that are more integrated into the global value chains should spend higher levels of R&D expenditure to enhance their innovation capabilities in order to acquire higher profitability, value-added and output capacity by moving towards more upstream industries. (b) Industrial policymakers in China should aim to provide more subsidies and enact tax reduction reform packages for downstream firms that are more integrated in global value chains so they could invest in R&D and innovate, ultimately allowing them to succeed at moving from downstream stages towards more upstream ones in the value chains. (c) In terms of the accessibility of banking loan provisions, it is necessary for China's industrial policymakers to place more priority on the provision of banking loans to those firms in the downstream and more global value chain trade-oriented industries instead of being too policy loan biased towards large state-owned enterprises (SOEs).

5  |  CONCLUSIONS

This paper constructs a simple dynamic model to formalise the micro-level mechanism of industrial upgrading along the value chains. Our model is the first attempt in the literature to integrate the sequential production framework with industrial upgrading works that have been widely discussed in the regional studies and management literature. Our model illustrates the relevance of the pricing, cost, profitability and output dynamics of firms’ upgrading process along the value chains. In particular, we first find that the pricing level will evolve to a higher level when firms upgrade from downstream to relatively more upstream stages. Second, the output level diminishes when firms upgrade from low value-added downstream stages with a higher mistake rate to high value-added upstream stages with a lower rate of mistakes, indicating that there exists an output-price trade-off during the industrial upgrading process along the value chains. Third, the cost level is lower in the upstream stages, because those stages are normally dominated by R&D-intensive firms with higher economic rewards, but at the same time they have the features of tremendous cost reduction activities such as production innovation. Fourth, we demonstrate that profitability level moves higher after firms upgrade from downstream stages to upstream stages, because firms in upstream industries are normally capital-intensive and high value-added.

This research also derives the conditions under which these firm-level dynamics exist along the value chains, including that a higher profitability of upstream firms does not hold. In order to sustain

5 See Appendix Tables C1 and C2 for the full list of China's industries with GVC = 1 vs. 0.
higher profitability for upstream firms, we demonstrate that three conditions must be satisfied. (a) The increasing rate of sunk cost (including R&D expenditure) over sequential stages of production cannot be sufficiently large (endogenous sunk cost effect). (b) The decreasing rate of change of intermediate input demand with respect to the price set by firms at the production stage cannot be sufficiently high (intermediate input price effect). (c) The decreasing rate of change of intermediate input demand with respect to the pricing dynamics over the sequential stages of production cannot be sufficiently large (sequential pricing uncertainty effect).

In terms of other firm-level dynamics apart from the profitability variation along the value chains, first, the total cost level is lower when firms climb from downstream stages to relatively more upstream stages in the value chains if and only if the decreasing rate of change of input demand with respect to the price set by firms at the production stage is sufficiently large. Second, the output level goes higher when the downstream firms move towards relatively more upstream stages if and only if the decreasing rate of change of input demand with respect to the price set by firms at the production stage is not sufficiently high. Third, the price level decreases when the firm at the production stage moves from downstream to relatively more upstream stages. Our findings herein present suggestive empirical evidence and can help initiate policy discussions focusing on China's industrial development strategies in order to further corroborate the theories proposed by this paper.

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CONFLICTS OF INTEREST
All authors declare that they have no conflict of interest.

ETHICAL APPROVAL
This paper does not contain any studies with human participants or animals performed by any of the authors.

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Data are available from the authors upon request.

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REFERENCES


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