Endogenous fragmented technology and optimal offshoring in large civil aircraft production

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Abstract

This paper is motivated by two observations in the large civil aircraft (LCA) industry. (1) Boeing and Airbus are significantly different in the degree of offshoring. (2) The degree of offshoring also changes among different aircraft models. To offer an explanation, this paper focuses on issues related to fragmentation. Existing literature has established the tie between fragmented technology and offshoring. However, it is assumed that production can be fragmented readily and at no cost; and only exogenous global economic factors have impact on the degree of fragmentation. This model distinguishes itself from others by incorporating endogeneity in fragmentation. A final-good firm can spend on R&D specifically for its own fragmented technology. As a result, the final-good firm can optimally choose the portion of components to be offshored. A strategic trade policy model is used to show that the degree of offshoring depends on the firm's own cost of production, the host country's cost of production, the global state of technology as well as the government trade policies. In particular, export subsidy and subsidy on R&D of fragmented technology are shown to be policy substitutes.

Keywords: Fragmentation; Offshoring; Outsourcing; Aircraft; Export subsidy; R&D subsidy; Boeing; Airbus

JEL classification: F12; F13; F23; L13

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1. Introduction

Boeing, has long been competing with its one-and-only rival, Airbus, in the large civil aircraft (LCA) market.[1]

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[1] Large civil aircraft (LCA) is a term used by the WTO. Boeing refers to them as "commercial airplanes" and Airbus calls them "passenger aircrafts".

Table 1 shows that for every size of plane that Boeing creates, Airbus develops a match, or vice versa.

To gain competitive edge, both Boeing and Airbus engage in offshoring. However, they engage in different degree of offshoring in their competing products.

Table 1
Large civil aircraft counterparts of Boeing and Airbus

	Boeing Model (year of first flight)	Airbus Model (year of first flight)
Jumbo	747 (1969)	A380 (2005)
Large Wide-Body	777 (1994)	A340 (1991)
Midsize Wide-Body	787 (2009)	A350 (2013)
Midsize Wide-Body	767 (1981)	A330 (1992)
Narrow-Body	737 (1967)	A320 (1987)

Source: Seattle Times (Gates, 2011).

Table 2. Boeing's Production of Major Aircraft Parts[a]

Launch year	1963	1966	1969	1981	1982	1994	2004
Aircraft model	727[b]	737	747	757[c]	767	777	787
Wings	D	D	D	D	D	D	F
Inboard flaps	D	F	F	F	F	D	F
Outboard flaps	D	F	F	F	F	F	F
Engine nacelles	D	D	D	D	D	D	D
Nose	D	D	D	D	D	D	D
Engine strut	D	D	F	D	D	D	D
Front fuselage	D	D	D	F/D	F	F	F/D
Center fuselage	D	D	D	F/D	F	F	F
Center wing box	D	D	F	D	D	F	F
Keel beam	D	D	D	D	D	F	F
Aft fuselage	D	D	D	D	F	F	D
Stabiliser	D	F/D	D	D	F	D	F
Dorsal fin	D	D	D	F	F	F	D
Vertical fin	D	F/D	D	D	F	D	D
Elevators	D	F	D	F	F	F	F
Rudder	D	F	D	F	F	F	F
Passenger doors	D	D	D	D	F	F	F
Cargo doors	D	D	F	F	F	F	F
Section 48	D	F/D	F/D	D	F	F	D
# of parts from foreign sources	0	7	6	8	13	12	12
% of foreign content	0%	37%	32%	42%	68%	63%	63%

[a] D = domestic production; F = foreign production; F/D = shared production.
[b, c] out-of-production models
Source: MacPherson and Pritchard (2003); Boeing; author's calculations.

Fig. 1 shows how Boeing and Airbus produce their newest LCA counterparts – 787 and A350 respectively. Boeing adopts two modes of offshoring - outsources 53% of 787 parts to foreign suppliers and produces 10% through foreign subsidiaries. This makes a total of 63% of offshoring. In contrast, Airbus outsources 16% of A350 parts to suppliers located outside EU countries and does not produce any A350 part through foreign subsidiaries, so there is only 16% of offshoring.[2] In the production of their newest LCAs, Boeing offshores 47% more than Airbus does.

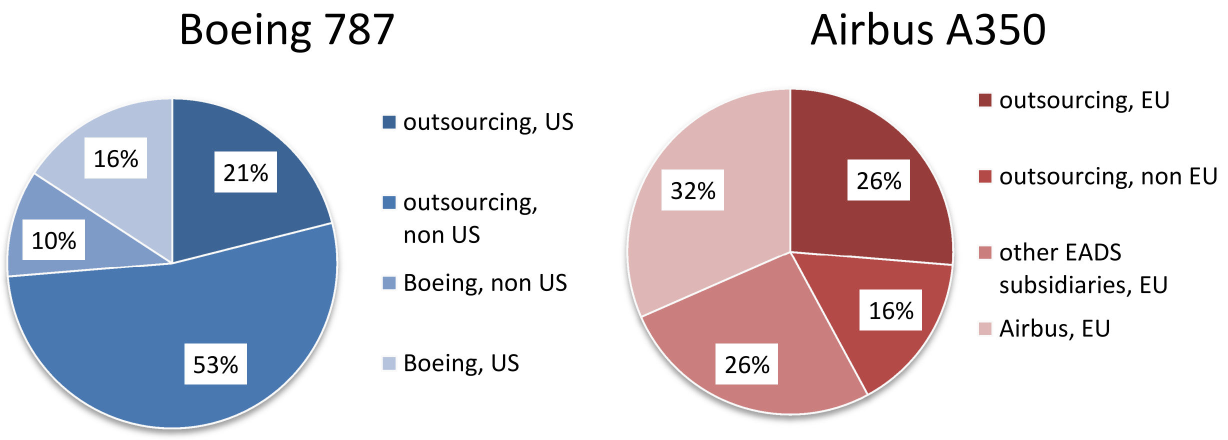

Fig. 1. Production organization of Boeing 787 and Airbus A350. Note: Major airplane parts are defined in Table 2. Sources: Boeing, Airbus and their suppliers; author's calculations.

Fig. 2 helps us better understand how an aircraft is assembled. In particular, it illustrates in details where the major aircraft parts of 787 are built. Fig. 2 also provides a source for author's calculations in Table 2.

The degree of offshoring is not only different across the companies, but also different across aircraft models.

Table 2 is an updated version of the table presented in MacPherson and Pritchard (2003). It shows the domestic content and the foreign content of each Boeing LCA. Of the nineteen major aircraft parts, foreign content takes up 0% of 727, 37% of 737, 32% of 747, 42% of 757, 68% of 767, 63% of 777 and 63% of 787. This shows that offshoring has grown in newer models.

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[2] Airbus has sites located in four EU countries: France, Germany, the UK and Spain. Production of these sites is considered to be in-house production of Airbus. Airbus is a subsidiary of EADS. Some A350 parts are produced by other EADS subsidiaries located in France and Germany. Judging from their proximity and ownership link to Airbus, I consider production by these EADS subsidiaries to be in-house production rather than offshoring.

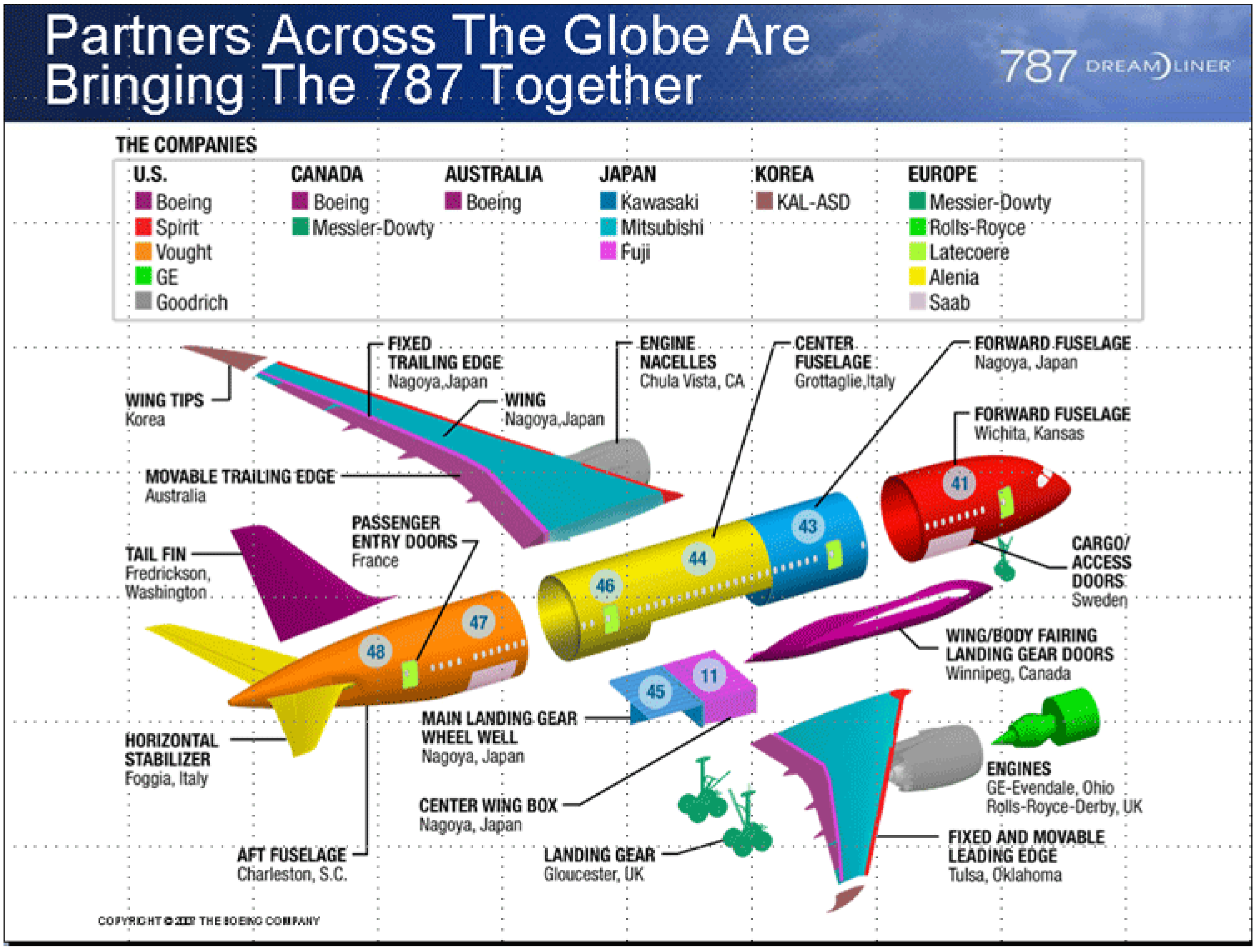

Fig. 2. Fragmentation of Boeing 787. Source: Boeing.

Two related questions are raised here: (a) Why do the aircraft companies engage in different degrees of offshoring in competing products? (b) Why is the degree of offshoring different across aircraft models? There are many possible explanations.[3] This paper focuses on those related to production fragmentation.

Following Deardorff (2001), fragmentation refers to "the splitting of a production process into two or more steps that can be undertaken in different locations but that lead to the same final product" in this paper. In other words, fragmentation is *not* offshoring, but fragmentation enables offshoring.

The difference in the degree of offshoring across aircraft models can be explained by the various factors of globalization. Advance in transportation and telecommunication technologies

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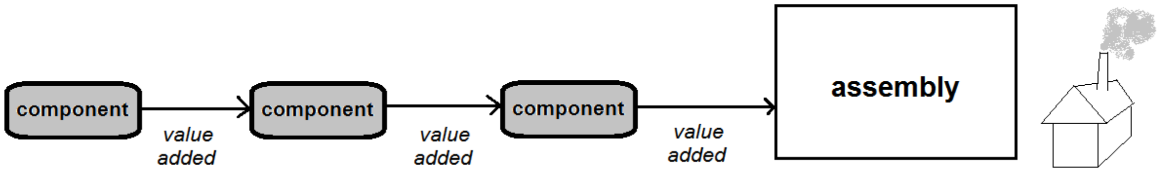
[3] For example, there are numerous studies on the role of the host countries in offshoring. Among them are Basile, Castellani and Zanfei (2008) and Mutti and Grubert (2004). Eckel and Egger (2009), Lommerud, Meland and Straume (2009), Swenson (2005) and Zhao (2001) focus on bargaining between multinational firms and local labor unions affects offshoring. Antràs (2003), Conconi, Legros and Newman (2012) and Ornelas and Turner (2008) apply contract theory. Antràs (2003) and Ornelas and Turner (2008) analyze how incomplete contract between firm and foreign suppliers has an impact on offshoring. Conconi et. al. (2012) look at how incomplete contract between manager and firm determines offshoring. These areas of studies are beyond the scope of this paper.

lowers the cost of coordination between the aircraft companies and their suppliers and subsidiaries. Consequently, offshoring in newer aircraft models are less costly than older ones.

In Jones and Kierzkowski (1990)'s language, lower coordination cost leads to more frequent use of "service links" between "production blocks". (See Fig. 3 for visualization.) The degree of fragmentation should increase. These global economic factors are *exogenous* determinants of fragmentation.

Panel (a). snake fragmentation



Panel (b). spider fragmentation

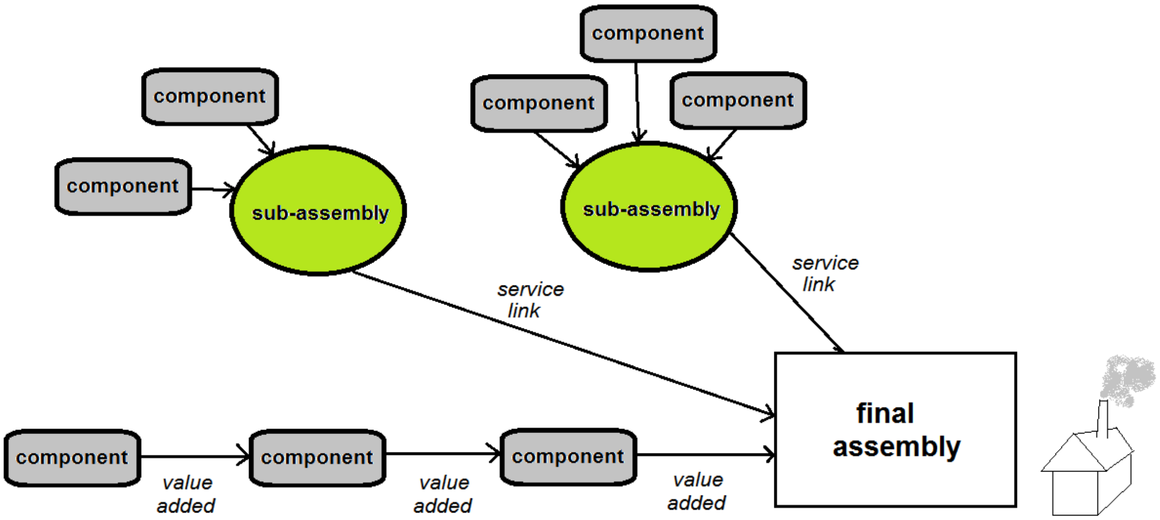


Fig. 3. Two modes of fragmentation – "the snake" and "the spider".

What are new in this paper are the *endogenous* factors of fragmentation. Boeing and Airbus are gigantic multinational corporations that produce some of the most high-technology products in the world. They have resources to develop their own production technology that directly determines fragmentation.

For example, the newest models, 787 and A350 are known for material evolution in their designs. The use of composite material makes the aircrafts lighter and more fuel efficient. At the same time, material evolution makes it possible to produce parts as single-piece items. At Boeing development center in Seattle, single-piece parts such as "a 7 m long by 6 m wide section of the fuselage" are constructed for testing (Marsh, 2005).

These single-piece parts can be made and shipped relatively easily and cheaply from suppliers and subsidiaries to the company's base for final assembly. In fact, it is by the aircraft company's own product design that production can be fragmented. That is, fragmentation is not possible without some "fragmented technology" developed by the aircraft company. For this reason, we will consider fragmentation as being determined endogenously by an aircraft company's investment on research and development (R&D).

Why the aircraft companies engage in different degrees of offshoring in competing products is more mysterious. Boeing and Airbus are similar in many ways. They have basically equal global market share. The two appear to be equally advanced in technology. The competing products, such as 787 and A350 are developed in almost the same time period that the companies are subject to the same global state of technology. Both companies are based in countries where wages are higher than the rest of the world and both suffer occasional labor strikes and delivery delays.

If despite of all these, there truly exist firm-specific characteristics, the companies may differ in their costs of production. This may explain how the degree of offshoring is different because their incentives for cost-saving offshoring in low-cost countries are different. However, it is doubtful that these firm-specific characteristics can explain the huge 47% difference in offshoring shown in Fig. 1.

Another explanation is to add the US government and the EU governments to the picture. Any export subsidy granted to Boeing by the US government or to Airbus by the EU governments distorts competition between the companies. If the amount of subsidies granted to the companies are different, their production organization will also be different. That is, the degree of offshoring should be different across the companies.

However, this explanation is not adequate. Both the US and the European Communities are members of the WTO and export subsidies are strictly prohibited. The recent trade disputes between Boeing and Airbus is "the biggest, most difficult and most expensive in WTO history", but the subsidies involved cannot be easily detected as "export subsidies" ("A dogfight," 2009). The tax and non-tax incentives granted to Boeing by state governments are considered to be "export subsidies". Others such as the R&D subsidies granted by NASA and the Department of Defense constitute "specific subsidies". The "launch aids" granted by the EU governments, contingent upon Airbus' export performance, constitute "export subsidies". Others such as cheap loans, provision of infrastructure and R&D grants are considered to be "specific subsidies" ("WTO Dispute," 2013). Motivated by these facts and the R&D of "fragmented technology" explained above, this paper naturally provides analysis on both export subsidy and R&D subsidy.

2. Related literature

The topic of fragmentation has been well explored. Arndt and Kierzkowski (2001) define fragmentation as "cross-border component specialization and production-sharing". Patterns of intra-product trade are analyzed through Ricardian and Heckscher-Ohlin models. It is shown that exploiting comparative advantage at the level of component production is welfare-enhancing.

An interesting extension of the models is performed by Van Long, Riezman and Soubeyran (2005). Services are considered to be a factor in production of components. Under free trade of services, advanced economies tend to offshore less service-intensive components to developing economies.

Jones and Kierzkowski (1990) emphasizes on the role of “service links” between “production blocks”. Their subsequent empirical study in Jones, Kierzkowski and Lurong (2005) confirms the theory’s predictions that trade in parts and components expands as services become less costly. Jones and Kierzkowski (1990) are some of the first ones to formally map out the pattern of fragmentation.

Baldwin and Venables (2013) investigate the relation between the engineering of the production process and offshoring. The two extreme modes of fragmentation are called “the snake” and “the spider”. Fig. 3 illustrates the two modes of fragmentation, slightly. I have slightly altered their figure so that it explains the present model better. It is obvious that production by the aircraft companies follow the “spider” mode. According to Baldwin and Venables (2013), the predictions of trade volume of the fragmented stages are different for the two modes, but lower costs of coordination, management, etc. increase the trade of the stages in both fragmentation modes.

Harms, Lorz and Urban (2012) describe the production chain to be a predetermined sequence of steps that can be offshored. That means Harm et. al. (2012) consider “the snake” mode of fragmentation. The highlight of their paper is to allow “offshoring costs” (such as coordination costs) to vary along the production chain non-monotonically. The shape of the offshoring costs function depends on heterogeneity of the steps, length of the production chain and general improvement of communication and information technology. A competitive firm has cost advantage in a step if factor costs are lower than offshoring costs. However, unless transportation cost is relatively low, a competitive firm does not offshore all the steps that the foreign country has cost advantage in. Typically, a firm either produces all steps at home or offshores almost all steps.

Recent studies on the topic of offshoring mainly adopt models of heterogeneous firms due to Melitz (2003).

Antràs and Helpman (2004) employ a north-south model. Heterogeneous final-good producers based in North decide on whether to integrate the production of intermediate inputs or outsource them, and whether to do so locally or overseas. It is shown that the more productive firms offshore to the South.

The empirical studies of Aw and Lee (JIE 2008), Tomiura (2007), Yasar and Paul (2007) and Yeaple (2009) also confirm that the most productive firms invest in foreign affiliates (through FDI) whereas the least productive firms do not offshore.

Grossman, Helpman and Szeidl (2006) has a similar model with two symmetric countries of North (called “East” and “West”) and one country of South. Given the choice of three locations to produce intermediate inputs and conduct assembly, they show that the most productive firms in East and West offshore entirely to South and the least productive firms do not offshore. Since East and West are symmetric that both have higher variable costs than South, it is not optimal for firms in East to offshore to West, or vice versa.

More recently, Du, Lu and Tao (2009) extend this framework to analyze firms’ “bi-sourcing” (both outsourcing and insourcing) option. With bi-sourcing, a source firm is in better bargaining position due to the competition between the suppliers and subsidiaries.

Note that the interpretation of my results and those in models of heterogeneous firms can be very different. First of all, in Melitz (2003)’s firm heterogeneity model, differences in productivity translates to differences in marginal cost of production across firms. My model assumes away firm heterogeneity and instead considers the two final-good firms, Boeing and Airbus, to be ex ante identical (in their marginal costs of production). This assumption is based on the similarities of the two companies' global market share, cost of production, access to technology and resources, etc.[4]

Second, at the firm level, their models show a final-good firms' choice of *whether or not* to offshore. In contrast, this paper asks the question *how much* a final-good firm offshores.

In their models, the degree of offshoring is measured at the industry level. Their models apply to a monopolistic competition market structure with each firm deciding whether to offshore. The degree of offshoring is the volume of "intra-industry trade" of the industry as a whole in the country of North.

In the present framework, there is only one aircraft company in each source country. The degree of offshoring can be measured by the foreign content (by aircraft parts) of the LCAs produced by an aircraft company. My paper offers an even closer look at the foreign content of a LCA model. That is, the scope is narrowed from "intra-industry trade" to "intra-product trade".

More importantly, my paper uses an oligopoly model instead because it better describes the structure of the LCA market. The strategic interaction between the source countries (East and West), namely the US and the EU is highlighted. The role of the host country (South) is less of a focus.

Chen, Ishikawa and Yu (2004) and Ishikawa, Morita and Mukunoki (2010) are the two recent papers that use an international duopoly model to analyze issues of offshoring.

In Chen et. al. (2004), two firms are located in two different countries. Each firm produces both a final good and an intermediate good. The twist is that each firm has the option to buy the intermediate good from the rival firm. As a result there is a "collusive effect" that, each firm outsources the intermediate good in order to raise the prices of both the intermediate and the final goods. Then, they proceed to analyze the different impacts of trade liberalization in the intermediate-good market versus the final-good market.

Ishikawa et.al. (2010) set up the model such that a firm has the option to outsource post-production services to the rival firm or provide the services through foreign subsidiaries. Trade liberalization in service FDI is shown to be welfare-improving.

A number of studies emphasize the relationship between R&D and offshoring.

Ethier and Markusen (1996) and Sener and Zhao (2009) essentially use a North-South model such that firms in North compete in R&D investment to develop a new product. Technology diffusion or the so-called "spillover effect" to South affects the winner firm's decision to offshore.

Dated back in early 80s, Brander and Spencer provide a framework for analyzing strategic trade policy. In Brander and Spencer (1985), two rival firms located in two countries correspond to two governments. In a noncooperative equilibrium, each government use export subsidy to support the domestic firm and discourage the foreign firm.

In Brander and Spencer (1983), the two rival firms compete in both production and R&D. It is shown that optimal export subsidy is positive but optimal R&D subsidy is negative. R&D is taxed because of the bias it produces and the failure to minimize cost at the presence of R&D. My model produces similar results that the policy appears to be "policy substitutes".

In Brander and Spencer (1983), the cost function is not specified. In my model, each company's R&D is specifically for its own fragmented technology. Hence, my model has a specific cost function where the spending on R&D of fragmented technology has to enter a certain way.

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[4] A 787-9 costs US$243.6 million while a A350-800 costs US$245.5 million in 2012. The costs are almost equal, especially when currency fluctuations and inflation are accounted for.

Below is a brief literature review of some recent analyses on strategic trade policies.

In Lee and Wong (2005)'s model, there are two firms in each country. One produces the final good and one produces the intermediate good. In addition to the two stages in Brander and Spencer (1985)'s model, there is a stage for the production of intermediate good. Both the final good and the intermediate good are subsidized. Vertical integration happens if the final good and the intermediate good are produced under one management. Lee and Wong (2005) show that if at least one country has vertical integration, subsidy on the final good is welfare improving.

Liao and Wong (2009) investigate competition between advanced North and developing South. Technology is developed in North but there is positive "spillover" to South. Strategic policy analysis applies to the R&D subsidy imposed by the Northern government and intellectual property rights protection policy by the Southern government. Their model shows that unilateral policy is less optimal than bilateral policies.

In order to answer the central questions (a) and (b), this paper has to extract elements from three strands of literature – fragmentation, optimal offshoring and strategic trade and industrial policies. When doing so, this paper introduces an underexplored element – endogenous fragmented technology.

3. The model

Consider two countries – the domestic country and the foreign country. There is one final-good firm in the domestic country, called "D" and one in the foreign country, called "F". The two firms compete in the production of a homogeneous product.

Let's assume that there is a single global market for the product. This assumption is justified by the fact that the consumers of aircrafts are mainly airlines. Airlines' operation is multinational in nature, so it is reasonable to consider global demand instead of national demand. Further assume that transportation cost is zero.

The quantity demanded of the product s denoted as X and so the demand is $P = P(X)$. The first and second derivatives of $P(X)$ has standard properties such that $P'(X) < 0$ and $P''(X) < \xi$, where ξ is a sufficiently small positive number.

Suppose final-good firm i's output is q^i, where $i = D, F$. Superscript i will be used to denote variables associated with the domestic and the foreign countries hereafter. Total supply is $Q \equiv q^D + q^F$. In equilibrium, $X = Q = q^D + q^F$.

Production process follows "the spider" mode (as illustrated in Fig. 3). If final-good firm i produces the components in-house, the marginal cost cost for that segment of production processes is α^i.[5] Let's assume that the final-good firms are ex ante identical. If neither of them engage in offshoring and there is no government intervention, their marginal cost of production should be identical. Hence, assume $\alpha^D = \alpha^F = \alpha$. Let's also assume α to be independent of output levels.

Note that comparative static is not derived for α because this would mean the production costs of the final-good firms are governed by some common forces. However, this is not our assumption. Rather, our assumption is based on the even competitiveness of the two aircraft companies, which may be due to their long-term competition, the way they gain access to world resources, etc. As a result, they are "natural duopoly" in the global market.

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[5] Final assembly is considered as a "component" here, in the sense that it is simply one of the stages of production.

If fragmented technology is available to a final-good firm, the firm will offshore all the components (as single-pieced subparts) to a low-cost country. Assume the marginal cost for that portion of production processes is β in the host country. The host country has cost advantage in the production of subparts, so $\beta < \alpha$.[6]

Assume the portion of fragmented production to be $f^i \in [0,1]$, and so $1 - f^i$ is the portion produced in-house in firm i. The (effective) marginal cost of production of the final good is

$$c^i = \alpha\left(1 - f^i\right) + \beta f^i \tag{1}$$

This says if the firm i produces all components in-house, $f^i = 0$, then marginal cost equals final-good firm i's own cost of production, $c^i = \alpha$. If firm i offshores all components, $f^i = 1$, then marginal cost equals host country's cost of production, $c^i = \beta$.

The following sections show how firms D and F compete in the final-good market in a Cournot fashion. Their competition depends on whether the firms can endogenize the fragmented technology or not. The functional form of f^i allow us to incorporate such endogeneity.

4. Fragmented technology

4.1 Exogenous fragmented technology

If the fragmented technology is only determined by some exogenous global economic factors, $f^i = \bar{f}^i(A)$ where is the state of technology. $A > 0$. A captures the international cost of telecommunication, the coordination cost of service links, etc. Note that even though transportation cost of components is not modeled explicitly, if there is a drop of transportation cost, its effect should show up as an increase of A.

An increase of A raises the degree of fragmentation, so $\bar{f}_A^i > 0$ where subscript denotes partial derivative $\partial \bar{f}^i / \partial A$. Since f^i is bounded by an upper bound 1, assume that $\bar{f}_{AA}^i < 0$.

Then the competition between firm D and firm F reduces to a standard model of strategic trade policy except that the marginal cost is now

$$c^i = \alpha[1 - \bar{f}^i(A)] + \beta \bar{f}^i(A) \tag{2}$$

There is a two-stage game in the standard model:

- In stage 1, the domestic government and the foreign government provide export subsidy to their local firm simultaneously in a non-cooperative fashion.
- In stage 2, firms D and F compete in a Cournot sense in the final-good market.

The standard results are widely discussed in the literature.[7] The basic result is that a decrease of its own marginal cost or an increase of export subsidy of its own country raises the production of a firm, but lowers the production of its rival firm. Optimal export subsidy found in the stage 1 is positive. Positive export subsidy is desirable because it improves the position of the local firm, gaining market share and profits under a noncooperative equilibrium.

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[6] As discussed in the introduction, the role of the host country in offshoring is not the focus of this paper. Therefore, it is assumed that there is only one host country without loss of generality.

[7] Readers can survey Brander and Spencer (1985) for details.

Note that α, β and A have impact on output levels only through their effects on c^i. Therefore, their effects of on output levels can simply be found by multiplying the effect of c^i to the derivative of c^i with respect to the parameter of interest.

As shown in the next subsection, the results are not the same once we introduce endogeneity in the fragmented technology.

4.2 Endogenous fragmented technology

Alternatively, a final-good firm can carry out R&D of its own fragmented technology. Suppose firm i's spending on R&D is k^i, then the degree of fragmentation becomes $f^i = f^i(A, k^i)$. Just as previously assumed, $f_A^i > 0$ and $f_{AA}^i < 0$. Similarly, further assume that $f_k^i > 0$ and $f_{kk}^i < 0$. Also, since $f^i \in [0,1]$ $f^i(A, 0) = 0$ and $\lim_{k\to\infty} f^i(A, k) = 1$.

Therefore, the general functional form is

$$f^i(A, k^i) = 1 - \frac{1}{(1 + m^i k^i)^{n^i A}} \tag{2}$$

where m^i and n^i are firm-specific parameters. m^i and n^i dictate the firm's capability of converting technology into new production formation. Particularly, m^i can be thought of as "fertility" of firm i's R&D on fragmented technology.

Fig. 4 plots the function $f^i = f^i(A, k^i)$ against k^i. An advancement of the state of technology leads to a rise of the degree of fragmentation for all levels of a firm's own R&D spending. Thus, an increase of A shifts up the curve of $f^i(A, k^i)$.

The marginal cost becomes

$$c^i = \alpha[1 - f^i(A, k^i)\,] + \beta f^i(A, k^i) \tag{3}$$

And there is an additional stage in the game:

- In stage 1, the domestic government and the foreign government provides export subsidy and R&D subsidy to their local firm simultaneously.
- In stage 2, firms D and F chooses the levels of R&D of fragmented technology simultaneously.
- In stage 3, firms D and F compete in a Cournot fashion in the final-good market.

The three-stage game can be solved by backward induction. Let's look at stage 3 first. Final good firm i chooses output to maximize its profit:

$$\pi^i = P(q^D + q^F)q^i - c^i q^i + s^i q^i - k^i + u^i k^i \tag{4}$$

taking k^i as given because in this stage, spending on R&D by a final-good firm is considered to be a fixed cost. The prior actions of the government, s^i, the export subsidy and u^i, the R&D subsidy provided are also taken as given. The exogenous variables throughout the model are α, β and A.[8]

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[8] $\pi^i = \pi^i(\alpha, \beta, A, q^D, q^F, k^i, s^i, u^i)$.

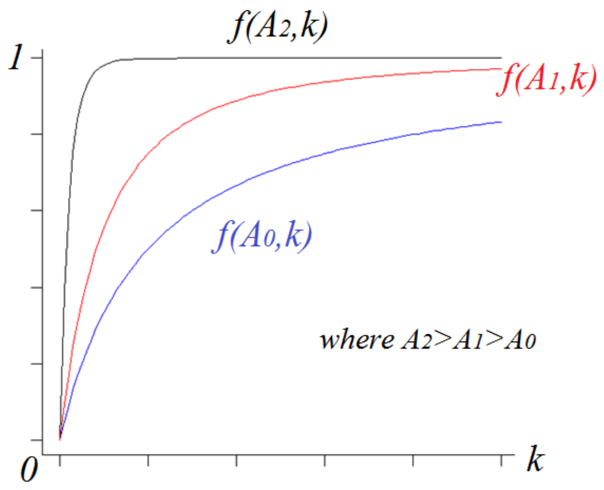

Fig. 4. Illustration of the fragmentation function.

The first-order conditions of the maximization problems of the two firms are

$$P'q^i + P = c^i - s^i = \alpha[1 - f^i(A,k^i)] + \beta f^i(A,k^i) - s^i \tag{5}$$

where again, $i = D, F$. The first order conditions give two reaction functions. Solving the reaction functions produce the Nash equilibrium output levels. Using tilde to denote Nash equilibrium solutions, $\tilde{q}^i = \tilde{q}^i(\alpha, \beta, A, k^D, k^F, s^D, S^F)$. Note that the Nash equilibrium output does not depend on u^D and u^F.

Differentiate conditions in (5) yield

$$\begin{bmatrix} P''\tilde{q}^D + 2P' & P''\tilde{q}^D + P' \\ P''\tilde{q}^F + P' & P''\tilde{q}^F + 2P' \end{bmatrix} \begin{bmatrix} d\tilde{q}^D \\ d\tilde{q}^F \end{bmatrix} = \begin{bmatrix} -1 \\ 0 \end{bmatrix} ds^D + \begin{bmatrix} 0 \\ -1 \end{bmatrix} ds^F + \begin{bmatrix} 1 \\ 0 \end{bmatrix} dc^D + \begin{bmatrix} 0 \\ 1 \end{bmatrix} dc^F \tag{6}$$

The determinant of the 2-by-2 matrix is $\widetilde{D} \equiv P'P''(\tilde{Q}) + 3P'^2 > 0$. $\widetilde{D}$ is assumed to be positive in the second-order conditions of the profit maximization problem. Solving condition (6), we obtain the effects of the export subsidies and the marginal costs. Where $i = D, F, j = D, F \text{ and } i \neq j$,

$$\frac{d\tilde{q}^i}{dc^i} = \frac{P''\tilde{q}^j + 2P'}{\widetilde{D}} < 0 \tag{7a}$$

$$\frac{d\tilde{q}^i}{dc^j} = -\frac{P''\tilde{q}^i + P'}{\widetilde{D}} > 0 \tag{7b}$$

$$\frac{d\tilde{q}^i}{ds^i} = -\frac{P''\tilde{q}^j + 2P'}{\widetilde{D}} > 0 \tag{7c}$$

$$\frac{d\tilde{q}^i}{ds^j}=\frac{P''\tilde{q}^i+P'}{\tilde{D}}<0 \tag{7d}$$

$$\frac{d\tilde{Q}}{ds^i}=-\frac{P'}{\tilde{D}}>0 \tag{7e}$$

The signs are the same as those in the standard model when fragmented technology is exogenous. A final-good firm produces more when its marginal cost is lower or when there is an increase of export subsidy, while its rival firm produces less. The effect of an export subsidy on total output is positive.

From condition (7), we can also obtain:

$$\frac{d\tilde{q}^i}{dA}=\frac{d\tilde{q}^i}{dc^i}\frac{dc^i}{dA}+\frac{d\tilde{q}^i}{dc^j}\frac{dc^j}{dA}=\frac{d\tilde{q}^i}{dc^i}(\beta-\alpha)\left(f_A^i\right)+\frac{d\tilde{q}^i}{dc^j}(\beta-\alpha)\left(f_A^j\right) \tag{8a}$$

$$\frac{d\tilde{Q}}{dA}=\frac{P'(\beta-\alpha)(f_A^D+f_A^F)}{\tilde{D}}>0 \tag{8b}$$

$$\frac{d\tilde{q}^i}{d\beta}=\frac{d\tilde{q}^i}{dc^i}\frac{dc^i}{d\beta}+\frac{d\tilde{q}^i}{dc^j}\frac{dc^j}{d\beta}=\frac{d\tilde{q}^i}{dc^i}f^i+\frac{d\tilde{q}^i}{dc^j}f^j \tag{8c}$$

$$\frac{d\tilde{Q}}{d\beta}=\frac{P'(f^D+f^F)}{\tilde{D}}<0 \tag{8d}$$

$$\frac{d\tilde{q}^i}{dk^i}=\frac{d\tilde{q}^i}{dc^i}\frac{dc^i}{dk^i}=\frac{d\tilde{q}^i}{dc^i}(\beta-\alpha)f_k^i>0 \tag{8e}$$

$$\frac{d\tilde{q}^i}{dk^j}=\frac{d\tilde{q}^i}{dc^i}\frac{dc^i}{dk^j}=\frac{d\tilde{q}^i}{dc^i}(\beta-\alpha)f_k^j<0 \tag{8f}$$

$$\frac{d\tilde{Q}}{dk^i}=\frac{P'(\beta-\alpha)f_k^i}{\tilde{D}}>0 \tag{8g}$$

for $i=D,F, j=D,F\ and\ i\neq j.$

The direction of the impact of A on a final-good firm's output level cannot be derived because of two opposite effects. The first term in (8a) is the "cost effect". Global technology advancement increases the degree of fragmentation and enable the firm to offshore a higher portion of its production process. Offshoring is cost-saving, so the "cost effect" of A is positive.

The second term in (8a) is the "rivalry effect". When there is an increase of the state of technology, the rival firm engages in higher degree of cost-saving offshoring. This raises the competiveness of the rival firm, and so has an adverse effect on the final-good firm itself. The "rivalry effect" of A is negative.

However, as shown in (8b) the total output is positively related to A.

The sign of the effect of β on a final-good firm's production is ambiguous by the same token. A reduction of cost in the host country encourages cost-saving offshoring, so the "cost effect" of β is negative in the first term of (8c).

The second term in (8c), on the other hand, is the "rivalry effect". When it is cheaper to offshore, the rival firm also does the same. This is favorable to the rival firm, and unfavorable to the final-good firm. The "rivalry effect" of β is therefore positive.

Summing the effects on total supply, nevertheless, β has an unambiguous negative effect.

Spending on R&D boost the production of a final-good firm, but reduce the production of the rival firm. The effect on total supply is positive.

Fig. 5 shows the effect of an increase of k^D on the Nash equilibrium output levels of firms D and F. The reaction functions of firm D and firm F are $q^F = R^D(q^F)$ and $q^D = R^F(q^D)$ respectively.

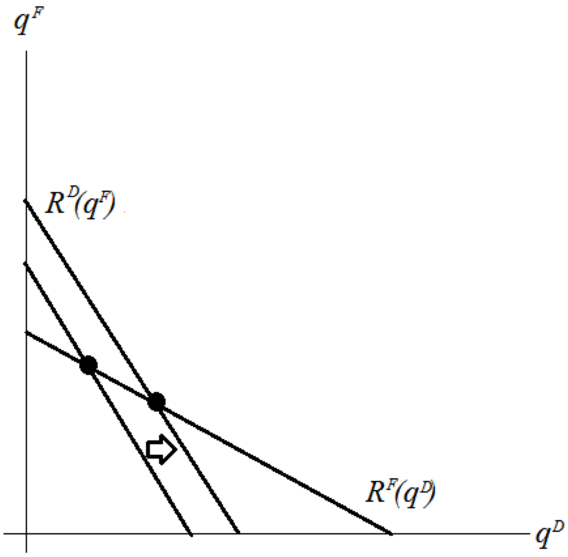

Fig. 5. Effect of an increase of R&D spending by the domestic firm.

We can also explore the effects of export subsidies, state of technology and host country's cost on price and demand of the global market:

$$\frac{d\tilde{P}}{ds^i} = \frac{dP}{dQ}\frac{d\tilde{Q}}{ds^i} = -\frac{P'^2}{\tilde{D}} < 0 \tag{9a}$$

$$\frac{d\tilde{X}}{ds^i} = \frac{dX}{dP}\frac{d\tilde{P}}{ds^i} = -\frac{X'P'^2}{\tilde{D}} > 0 \tag{9b}$$

$$\frac{d\tilde{P}}{dA} = \frac{dP}{dQ}\frac{d\tilde{Q}}{dA} = \frac{P'^2(\beta-\alpha)(f_A^D + f_A^F)}{\tilde{D}} < 0 \tag{9c}$$

$$\frac{d\tilde{X}}{dA} = \frac{dX}{dP}\frac{d\tilde{P}}{dA} = \frac{X'P'^2(\beta-\alpha)(f_A^D + f_A^F)}{\tilde{D}} > 0 \tag{9d}$$

$$\frac{d\tilde{P}}{d\beta}=\frac{dP}{dQ}\frac{d\tilde{Q}}{d\beta}=\frac{P'^2(f^D+f^F)}{\widetilde{D}}>0 \tag{9e}$$

$$\frac{d\tilde{X}}{d\beta}=\frac{dX}{dP}\frac{d\tilde{P}}{d\beta}=\frac{X'P'^2(f^D+f^F)}{\widetilde{D}}<0 \tag{9f}$$

The interpretation is straight-forward. An increase of export subsidy, an increase of the state of technology, a reduction of cost in host country or an increase of R&D spending of a final-good firm expand total production, drive down market price and raise demand. The R&D subsidy does not have any impact.

Next is to look at stage 2. Final-good firm i chooses the level of R&D in order to maximize the gain function. The gain function is defined to be the value of the profit function when the firm's output is chosen optimally:[9]

$$G^i(\alpha,\beta,A,k^D,k^F,s^D,s^F,u^i)\equiv P(\tilde{q}^i+\tilde{q}^j)\tilde{q}^i-\{\alpha[1-f^i(A,k^i)]+\beta f^i(A,k^i)\}\tilde{q}^i \\ +s^i\tilde{q}^i-k^i+u^ik^i \tag{10}$$

taking the policy parameters as given, the gain function can be differentiated with respect to k^i to yield the first-order condition:

$$\frac{4}{3}(\alpha-\beta)\tilde{q}^if_k^i=1-u^i \tag{11}$$

where $i=D,F$. The first-order conditions in (11) give reaction functions.

Fig. 6 plots the reaction functions of the R&D spending of the final-good firms, $k^D=r^D(k^F)$ and $k^F=r^F(k^D)$. The second derivatives of the gain function with respect to own R&D and rival's R&D are generally complicated, so the negative slope and concavity of the reaction functions are proved using some reasonable parameter assumptions. (See the Appendix for details.) These assumptions are used repeatedly to derive signage from this point on.[10]

The optimal level of R&D spending $\tilde{k}^i=\tilde{k}^i(\alpha,\beta,A,s^D,s^F,u^D,u^F)$g, can be solved from (11). Due to the functional form of $f^i(A,k^i)$, there can be multiple solutions.[11] Using reasonable values of A and k^i, it can be proved that positive solution for $\tilde{k}^i$ exists.

Note that given A, the degree of fragmentation increases with the spending on R&D. That is, $f_k^i>0$. In turn, the portion of production being offshored is directly determined by the degree of fragmentation. Once the optimal level of R&D spending is derived,

$$\tilde{f}^i=f^i(A,\tilde{k}^i(\alpha,\beta,A,s^D,s^F,u^D,u^F)) \tag{12}$$

can be thought of as the *optimal degree of offshoring* of final good firm i in this present model.

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[9] $G^i(\alpha,\beta,A,k^D,k^F,s^D,s^F,u^i)\equiv\tilde{\pi}^i=\pi^i(\alpha,\beta,A,q^D(\alpha,\beta,A,k^D,k^F,s^D,S^F),q^F(\alpha,\beta,A,k^D,k^F,s^D,S^F),k^i,s^i,u^i)$

[10] These assumptions are linear demand ($P''=0$), sufficiently large market size, f^D and f^F not too different and $f^if_{kk}^i+f_k^i<0$ for $i=D,F$. The last condition is satisfied if A and k^i are not too small.

[11] For example, setting $A=1$ yields a cubic equation that can cross the horizontal axis three times, so three solutions are found.

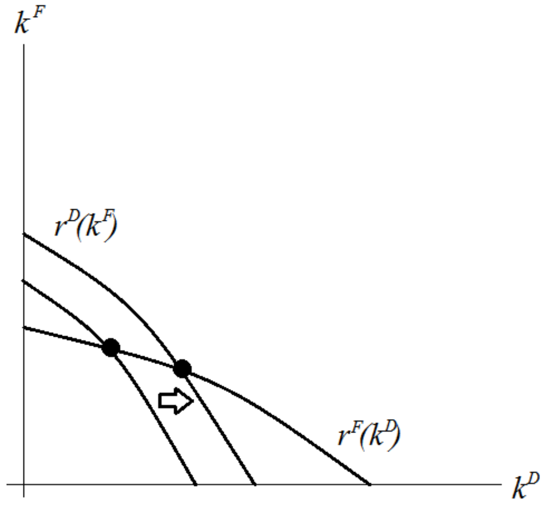

Fig. 6. Effect of an increase of export subsidy (or R&D subsidy)

The central questions asked in this paper are partly answered by (12).

First of all, the global economic environment reflected in α, β and A certainly has an effect on the level of offshoring. Boeing and Airbus can both optimally choose the levels of offshoring by spending on R&D of fragmented technology, taking into account the cost advantage of the host countries as well as the costs of coordinating their foreign suppliers and subsidiaries. Depending on how these factors change over time, the aircraft companies adjust their optimal level of offshoring when developing newer models.

On the other hand, both the US and the EU governments adopt export and R&D subsidies. These subsidies have crucial impacts on the optimal degrees of offshoring of the aircraft companies. As a result, the competition between Boeing and Airbus is extended to the governments. These policy effects are investigated in details below.

The second derivatives of the gain function with respect to R&D spending can be simplified to:

$$G_{ii}^{i} \equiv \frac{\partial^2 G^i}{\partial {k^i}^2} = \frac{4}{3}(\alpha-\beta)[\tilde{q}^i f_{kk}^i - \frac{2}{3}(\alpha-\beta)\frac{{f^i_k}^2}{P'}] < 0 \qquad (13a)$$

$$G_{ij}^{i} = G_{ji}^{j} \equiv \frac{\partial^2 G^i}{\partial k^i \partial k^j} = \frac{4}{3}(\alpha-\beta)^2 \frac{f_k^i f_k^j}{P'} < 0 \qquad (13b)$$

for $i = D, F, j = D, F\ and\ i \neq j$. Assume the second-order conditions to hold so that $\widetilde{H} \equiv G_{ii}^{i} G_{jj}^{j} - {G_{ij}^{i}}^2 > 0$. (See the Appendix for detailed derivation of the signs of (13).)

The impacts of the policy variables on R&D investment spending can be derived using conditions (13):

$$\frac{d\tilde{k}^i}{ds^i} = \frac{-\frac{4}{3}(\alpha-\beta)[\frac{\partial \tilde{q}^i}{\partial s^i} f_k^i G_{jj}^{i} - \frac{\partial \tilde{q}^j}{\partial s^i} f_k^j G_{ij}^{i}]}{\widetilde{H}} > 0 \qquad (14a)$$

$$\frac{d\tilde{k}^i}{ds^j} = -\frac{\frac{16}{3}(\alpha-\beta)^2\frac{\tilde{q}^i f_k^i f_{kk}^i}{P'}}{\widetilde{H}} < 0 \tag{14b}$$

$$\frac{d\tilde{k}^i}{du^i} = -\frac{G_{jj}^j}{\widetilde{H}} > 0 \tag{14c}$$

$$\frac{d\tilde{k}^i}{du^j} = \frac{G_{ij}^i}{\widetilde{H}} < 0 \tag{14d}$$

The sign of (14a) is proved in the Appendix. Not shown in (14) are the effects of A and β. Their influence on R&D spending is ambiguous for the same reasons discussed previously. The "cost effect" and the "rivalry effect" again move in opposite directions.

The influence of the subsidies on final-good firms' R&D spending also changes the optimal degrees of their offshoring. The impact is summarized in the following proposition:

Proposition 1. *The optimal degree of offshoring increases with the export and R&D subsidies granted by local government, but it decreases in response to the subsidies imposed by rival government.*

Finally, we arrive at stage 1, in which the governments choose export subsidies and R&D subsidies simultaneously and noncooperatively.

Define the net domestic benefit of country i to be

$$B^i \equiv \tilde{G}^i - s^i\tilde{q}^i - u^i\tilde{k}^i \tag{15}$$

which is the gain function with R&D spending chosen optimally minus the costs of the subsidies.[12] Government i maximizes B^i by choosing s^i and u^i taking the subsidies of the rival government as given.

The benefit function can be differentiated to derive first-order conditions. Setting the conditions equal zero and with some rearrangements,

$$s^i = P'\tilde{q}^i\frac{\left(\frac{\partial\tilde{q}^j}{\partial s^i}+\frac{\partial\tilde{q}^j}{\partial k^i}\frac{\partial\tilde{k}^i}{\partial s^i}+\frac{\partial\tilde{q}^j}{\partial k^j}\frac{\partial\tilde{k}^j}{\partial s^i}\right)}{\frac{\partial\tilde{q}^i}{\partial s^i}+\frac{\partial\tilde{q}^i}{\partial k^i}\frac{\partial\tilde{k}^i}{\partial s^i}+\frac{\partial\tilde{q}^i}{\partial k^j}\frac{\partial\tilde{k}^j}{\partial s^i}} - u^i\frac{\frac{\partial\tilde{k}^i}{\partial s^i}}{\frac{\partial\tilde{q}^i}{\partial s^i}+\frac{\partial\tilde{q}^i}{\partial k^i}\frac{\partial\tilde{k}^i}{\partial s^i}+\frac{\partial\tilde{q}^i}{\partial k^j}\frac{\partial\tilde{k}^j}{\partial s^i}} \tag{16a}$$

$$u^i = P'\tilde{q}^i\frac{\left(\frac{\partial\tilde{q}^j}{\partial k^i}\frac{\partial\tilde{k}^i}{\partial u^i}+\frac{\partial\tilde{q}^j}{\partial k^j}\frac{\partial\tilde{k}^j}{\partial u^i}\right)}{\frac{\partial\tilde{k}^i}{\partial u^i}} - s^i\frac{\frac{\partial\tilde{q}^i}{\partial k^i}\frac{\partial\tilde{k}^i}{\partial u^i}+\frac{\partial\tilde{q}^i}{\partial k^j}\frac{\partial\tilde{k}^j}{\partial u^i}}{\frac{\partial\tilde{k}^i}{\partial u^i}} \tag{16b}$$

for $i = D, F, j = D, F\ and\ i \neq j.$

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[12] $\tilde{G}^i = G^i(\alpha,\beta,A,k^D(\alpha,\beta,A,s^D,s^F,u^D,u^F),k^F(\alpha,\beta,A,s^D,s^F,u^D,u^F),s^D,s^F,u^i)$

Conditions (16) are four policy reaction functions. They can be solved simultaneously for optimal policies.

The signs of the optimal policies cannot be derived without some strict parameter assumptions that are not quite justified. However, (16) still provide important insights.

In (16a), the first term is positive. The second term is negative (positive) if u^i is positive (negative). That means any positive R&D subsidy reduces the optimal size of an export subsidy. If R&D of fragmented technology is taxed instead, it raises the optimal size of the export subsidy.

In parallel, the first term of (16b) is positive. The second term is negative (positive) if s^i is positive (negative). That means any positive export subsidy reduces the optimal size of a R&D subsidy. If production is taxed instead, it raises the optimal size of the R&D subsidy.

Thus, from the point of view of government i, the two subsidies are "policy substitutes". This result is in line with Brander and Spencer (1983).

Summarizing in a proposition:

Proposition 2. *In general, the signs of the optimal export subsidy and optimal subsidy on R&D of fragmented technology are ambiguous. However, we can be certain that the two subsidies are policy substitutes.*

This result provides insights to the observations in the LCA industry. Recall that export subsidies are strictly prohibited under the WTO's rules. Since R&D subsidies is a policy substitute to export subsidies, the US and the EU governments switched to R&D subsidy.

There are policy implications with regard to Proposition (2). As discussed in the introduction, the settlement of the trade dispute between Boeing and Airbus involves huge amount of resources from the US, the EU government as well as the WTO. This is because most of their subsidies constituted "specific subsidy" rather than "export subsidy". "Specific subsidy" is harder to be detected and defined case by case. Learning from the experience of the Boeing versus Airbus trade disputes, the WTO should re-define and distinguish "R&D subsidy" from other industrial policies that constitute "specific subsidy" in order to prevent any gray area in the rules.

5. Concluding remarks

From the data shown in this paper, we can observe different organizational structures and different extents of offshoring across the large civil aircraft (LCA) industry. Based on these observations, this paper emphasizes on two questions: (1) Why do Boeing and Airbus engage in different degrees of offshoring? (2) Why are there different degrees of offshoring in different aircraft models produced by the same company? The explanations that this paper offers are related to production fragmentation.

The answer to question (2) is easier. Many earlier studies explain the effect of global improvement of telecommunication, transportation, etc. as determinants of the degree of fragmentation. However, the role of a final-good firm in developing its own fragmented technology should not be ignored. This is especially true in the LCA industry as the two aircraft companies have access to tremendous amount of resources and are granted R&D subsidies.

Therefore, this paper offers a model in which fragmented technology is not only determined by exogenous global factors but also by a final-good firm's R&D on its own fragmented technology. In turn, since the host country has cost advantage in the components, the fragmented subparts can be offshored. In other words, once optimal R&D spending on fragmented technology is determined, the optimal degree of offshoring is also determined.

There are still more to answer question (1). The two aircraft companies appear to be similar in terms of market share, access to resources, cost of production, etc. Firm characteristics cannot adequately explain the huge difference in degrees of offshoring across the aircraft companies. However, the recent WTO disputes between Boeing and Airbus give us some clues. Both the US and the EU governments offer export subsidies and R&D subsidies.

Naturally, this paper uses a strategic trade model to analyze both export subsidy and R&D subsidy on fragmented technology. It is shown that the two subsidies are policy substitutes. This explains what we observe in the LCA industry. While the WTO has strict rules over “export subsidy”, R&D subsidy, which constitute a “specific subsidy” is not as easily defined. In the past decades, Boeing and Airbus are granted mainly “specific subsidy” rather than “export subsidy”.

Before I put a period to this paper, some extension ideas can be offered.

First, endogeneity in fragmented technology can be introduced easily into any cost function. This provides a lot of adaptability into different models. For example, it can be applied to other market structures other than oligopoly. It will be interesting to see how it can be incorporated in a model of heterogeneous firms. Based on the literature, I expect productivity of a firm to be positively related to its spending on R&D of fragmented technology, and so a more productive firm offshores to a larger extent.

Second, the present model does not display the role of the host country in offshoring. A North-South model may be used to show how fragmented technology is “spilt over” from the advanced North to the developing South through offshoring. For example, in the LCA industry, Spirit, a supplier of both Boeing and Airbus, has located some high-technology production of composite fuselage in developing countries such as Malaysia.

Finally, another possible extension is to allow for a final-good firm’s R&D spending on fragmented technology to enter the fragmentation function of another final-good firm. In such model set-up, issues such as free-riding on fragmented technology can be analyzed.

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