"Breaking the Mirror": Interface Innovation and Market Capture by Japanese Professional Camera Firms, 1955-1974

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Abstract

Improving an interface to increase control over interactions between existing product modules can create new product features which alter the basis of competition in mature (sub-)markets. We empirically examine the impact of interface innovation by new market entrants from Japan in the high-end, professional camera sub-market between 1955 and 1974. Prior to 1960, the industry architecture of the professional camera sub-market was modular, dominated by German specialist body and specialist lens manufacturers. This market structure changed due to the success of integrated Japanese start-ups who, from 1961, offered novel automated exposure features, facilitated by improving the existing interface between the camera body and lens, and by making this interface a proprietary standard. Their success broke the mirror between the industry architecture, which became vertically integrated, while the product architecture remained modular.

Keywords: interface innovation, mirror hypothesis, innovation, professional cameras.

JEL. O31, L60, C32.

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"Breaking the Mirror": Interface Innovation and Market Capture by Japanese Professional Camera Firms, 1955-1974

1. Introduction

The mirroring hypothesis links product modularity with organizational modularity. In a recent review, Colfer and Baldwin (2016) observe there are two categories of cases that violate the mirroring hypothesis: (1) integrated organizations which produce modular products, and (2) modular organizations which produce integrated products.

A key research question concerns the strategies which firms have employed in order to 'break the mirror'. The rich case study of the professional camera sub-market, presented in this paper, contributes to our understanding of the type of strategies used by new market entrants to capture markets, and which can change the industry to one in which there is a dominance of integrated organizations producing modular products (case 1, above).

During the late 1950s and 1960s, a number of new Japanese start-ups entered the professional camera sub-market and started to replace the existing mechanical aperture coupling lever[1] (the interface between lens and camera body) with an electrical interface. This enabled information from a light metering module to be passed, either to a simple servo control of aperture blades in the lens, or, alternatively, to a simple servo control of the shutter mechanism to ensure correct exposure.

[1] The aperture coupling lever was originally a purely mechanical interface between lens and body, controlling the opening of the lens aperture to ensure correct exposure for a given shutter speed.

By improving the specification of an existing interface among the interacting physical components that make up the camera, Japanese firms were able to offer new features ('service characteristics') to consumers, while simultaneously making these interface improvements proprietary. The first key feature offered to professional photographers was automated exposure (AE). AE was attractive to professional photographers because it speeded up the operation of picture taking. In particular, it was popular amongst sports, newspaper, and wildlife photographers who were using single lens reflex (SLR) cameras. Professional photographers, however, wish (then as now) to retain the option of complete control over all aspects of picture taking. They need to be able to revert back to completely manual operation, quickly and easily. This was reflected in the early AE cameras which, apart from the introduction of simple servo controls and electrical interface, did not change in terms of its modular architecture, or its modules.

The other aspect of this case study was the capture of the previously 'open' mechanical lens-body interface (the M42 screw thread interface) by a small set of proprietary (non-interoperable) bayonet lens-body interfaces with different configurations of electrical pin connectors that were introduced by those vertically integrated firms offering AE.

The importance of interfaces to modularization is highlighted in the mirroring hypothesis literature (e.g. Langlois and Robertson 1992; Langlois 2002). The direction of change in industry architecture can change towards greater specialisation and modularity, driven by the creation of new product modules and/or an increase in the number of interfaces between modules. This pre-supposes that standards are open and allow interoperability between modules. However, the literature on standards competitions has highlighted the competitive advantage which firms can gain from introducing proprietary, non-interoperable standards that force consumers to choose between the rival products offered by competing firms (e.g. Farrell and Saloner 1985; Swann 1987; Farrell and Saloner 1989). This changed the basis of competition in the industry, and the resulting shake-out of firms resulted in an industry structure dominated by vertically integrated firms.

Deploying data envelope analysis (DEA), this paper investigates the importance of AE in altering the innovation trajectory of the professional camera industry.

The paper is organised as follows. Section 2 provides an overview of the mirroring hypothesis literature. Section 3 discusses the competitive advantage of replacing a pre-existing interface design with a technological alternative. In the case of the post-war development of the professional camera market, this involved the replacement of a mechanical interface between lens and camera body modules with an electrical interface that could carry more information between these two modules. Using simple mechanical servo controls, this alternative interface facilitated the introduction of a new feature – automated exposure (AE). The case highlights the strategic advantages of integrated Japanese start-ups, and how these firms were able to exploit the weaknesses of the European modular specialists through their development of proprietary (non-interoperable) AE systems. The resulting standards competition drove out specialist body manufacturers who were unable to develop their own AE systems.

Section 4 discusses exposure and the artistic parameters of the photographer when determining exposure. This paves the way for an appreciation of the attractiveness of AE to the professional photographer, discussed in section 5. This helps one appreciate why and when the photographer would wish to use AE and when to switch back to manual operation. The need to quickly switch between automated and manual modes directly influenced the early design set-up of AE by manufacturers. This is highlighted in the discussion of section 6, which examines the technical design of AE, as introduced in 35mm SLR cameras. In section 6 we compare Design Structure Matrices (DSMs) (Steward, 1981) listing the key technical variables of a manual SLR camera, and the technical dependencies between those key variables, with that of early aperture-priority and shutter-priority SLR cameras. This highlights the (relatively) simple mechanical solutions that engineers came up with for achieving AE, given the user's desire to switch between AE and manual operation. The analysis helps to clarify AE as an example of a new product feature facilitated by interface innovation, in which the pre-existing modular design configuration was adapted, as opposed to an architectural product change or an integrative change.

Section 7 formally sets up our research hypotheses that the introduction of AE drove the industry dynamics following its introduction. Section 8 discusses the dataset and the statistical methods used to empirically test these hypotheses. We apply DEA to a dataset of 635 cameras listed in the annual Buyers Guide of *Amateur Photographer* magazine between 1955 and 1974 (inclusive). The results are reported in Section 9. Prior to the introduction of AE in 1961, the vast majority of cameras located on the efficiency frontier are manufactured by specialist modular European firms. After 1961 the efficiency frontier is increasing populated by cameras with AE, which were overwhelmingly produced by integrated Japanese firms. Section 10 concludes with a discussion of the implications of interface innovation for further research on standards, innovative product features, and the mirroring hypothesis.

2. Modularity and the mirroring hypothesis

The mirroring hypothesis links product modularity with organizational modularity, i.e. the division of labour and knowledge across firms within an industry (see recent reviews of the literature by Colfer and Baldwin (2016) and Sorkun and Furlan (2016)).

Sanchez and Mahoney (1996) first formulated the 'mirroring' hypothesis that standardized component interfaces in a modular product architecture provide a form of embedded coordination, which greatly reduces overt managerial control to achieve the coordination of product development. Subsequent contributors highlight varying aspects of this association. For example, Cabigiosu and Camuffo (2012) highlight the association between modular products and modular organizations, and Sorkun and Furlan (2017) report a direct relationship between product modularity and organizational modularity. For Lee and Berente (2012: p1428) "innovative efforts take place across organizations in a way that is generally isomorphic, or 'mirrors,' the structure of products that these firms produce"; for MacCormack et al. (2012: p1309) "loosely-coupled organizations will develop more modular designs than tightly-coupled organizations".

Ulrich (1995) defines a product architecture as "the scheme by which the function of a product is allocated to physical components" (*ibid*, p.420). Following Simon (1962), the development of modular product architectures is viewed to be a rational response to product complexity. There exists an 'ideal modular form' for any product, in which interdependent components are grouped into distinct modules, and there are no dependencies between these modules. Dependencies between components within a module cluster are assumed to incur a low cost, while those between components in different modules are assumed to incur a high cost.

The key advantage of a modular architecture is that improvements can be made to one module without needing to make changes to other modules (Simon 1962, 1976, 1978; Henderson and Clark 1990; Ulrich 1995; Ulrich and Eppinger 2008), and reciprocal interdependencies between modules are minimised by common industry standards for hardware and/or software interfaces (Parnas 1972; Langlois and Robertson 1992; Baldwin and Clark 2000).

The basic premise of the mirroring hypothesis is that, for any design, there is an efficient way to arrange the different modules and distribute work across a network of producers. What is more, firms in an industry search for an optimal set of arrangements over time and, as a consequence of organizational and product innovation, industry structure can change, sometimes dramatically.

Baldwin and Clark (2000) and Baldwin (2008) discuss the relationship between thick/thin crossing points at the boundaries of modules, transaction costs between firms, and the network of organizational ties in an industry. It is suggested that a modular system is based on the ability to standardize and count what is transferred across boundaries, and on a division of cognitive labour across different organizations (due to physical and cognitive limitations, no single organization can carrying out all tasks). Module boundaries should be located where (a) standardizing and counting what is being transferred is relatively easy and inexpensive, and (b) the common information needed on both sides of the transaction is minimized, i.e., the division of cognitive labour is greatest.

Baldwin and Clark (2000) refer to the costs of standardizing, counting, valuing and paying for goods as 'mundane transaction costs, and propose that interfaces ought to be created where mundane transaction costs are at their lowest. Given dependencies between product components (see above), product modularity affects transaction costs. Notably, thin crossing points at the boundaries of modules have low transaction costs, while thick crossing points in the interior of modules have high-transaction costs for firms.

Baldwin (2008) suggests that modularizations occur where transaction costs are low. New module boundaries therefore provide entry for competitors, and 'breakpoints' where vertically integrated firms and industries may split apart. Langlois (2003) predicts a trend in industry architecture that mirrors the tendency for modularity to increase over time in complex products. In a nascent industry, new firms tend to be vertically integrated as key new technological and other related knowledge tends to be scarce, and many of the problems involved in manufacture have not yet been resolved (also see Utterback and Abernathy 1975). Over time, the development of new interface standards enables specialisation in particular modules by firms, thereby gaining economies of scale in production, and this leads to a break down in vertical integration over time.

In their recent review of the literature, Sorkun and Furlan (2017) find that most early empirical studies found evidence supporting the mirroring hypothesis. Amongst those cases where there is both high product modularity and high organizational modularity, they find three rationales: low coordination costs, operational benefits, and high strategic flexibility.

Coordination costs can become too high for complex products. Adopting modular designs can be a means of reducing coordination costs, as standardized interfaces embed the information necessary to coordinate different actors efficiently. Empirical papers on aircraft (Argyres, 1999), automobiles (Fine et al., 2005), personal computers (Hoetker, 2006), and air-conditioning (Cabigiosu and Camuffo, 2012) suggest that adopting modular designs lowers coordination costs, as standardized interfaces embed the information necessary to coordinate different actors, enabling greater organisational modularity.

Various operational benefits have been attributed to high product modularity - high organizational modularity situations. For example, studies by Argyres (1999), Takeishi and Fujimoto (2001), and Hoetker et al. (2007) suggest standardized interfaces ensure a quality of externally sourced components, reducing monitoring costs for buyers. Galvin and Morkel's (2001) bicycle study indicates that specialization on specific modules can enable firms to develop more efficient processes, lowering sourcing costs.

Strategic flexibility is a third rationale. Organizational decoupling, facilitated by product modularity, helps the firm to mitigate operational risks and better meet customers' changing needs. In developing solutions for local customers, product development teams mitigate against unexpected problems. There is also power in combining capabilities with other development groups, to develop new product configurations.

There exist examples, such as IT hardware and software sectors (Schilling and Steensma 2001; Sturgeon 2002; MacCormack et al. 2012), stereo hi-fi (Langlois and Robertson 1992), certain banking products and services (Jacobides 2005; Consoli 2005), and automobiles (Ro et al. 2007) where an industrial sector initially comprised vertically integrated firms producing integrated products. The commercial success of new, modular products saw a rapid change in industry structure, with firms becoming specialised producers of specific modules.

More recent empirical studies have been more critical of the mirroring hypothesis. One criticism is that knowledge boundaries rarely match organizational and product component boundaries, especially for firms who are system integrators (Brusoni et al. 2001, and Brusoni and Prencipe, 2006). For a system integrator, it is essential not only to have knowledge of the technological trajectories of the various key components which make up a complex product but also the interdependencies between modules. Without this, an integrator will be unable to solve production problems, integration problems (Zirpoli and Becker, 2011), and/or deal with performance bottlenecks when developing the next generation of the product (Ethiraj, 2007).

Staudenmayer et al. (2005) observe that most of the interdependencies between components cannot be foreseen *ex ante* in the product design phase.

Organisational modularity limits scale and scope, even of lead firms, providing an incentive for new or existing firms to undermine it. Christensen (2002) and Christensen et al. (2002) suggest the incentive may be strongest in sub-markets where demanding consumers seek improved functionality that is difficult to attain within a modular industry structure. In such sub-markets, innovators may engage in 'module integration'. This involves the recombination, into a single module, of the functionality previously present in two or more modules. It enables engineers to maximise the degrees of freedom needed to "wring the best performance possible out of the available technology" (Christensen 2002, p.36). By contrast, a modular architecture inhibits engineers' degrees of freedom, keeping them from reaching the technological frontier. Fixson and Park (2008) show how the introduction of an integral architecture for click shifting gears enhanced bicycle performance and led, in a few years, to a vertically structured and near monopolistic bicycle industry dominated by the innovative firm. Other examples of modular integration include disk drives and Microsoft Office suite (Christensen et al., 2002), building facilities (Cacciatori and Jacobides, 2005), the single drum washing machine design that replaced separate washer and spinning drums (Smith 2009), and the substitution of the modular desktop and monitor PC by laptops and tablets.

This paper contributes to the recent literature by examining what can happen when there is innovation at a pre- existing interface. The prior literature has predominantly focused on the creation of new interfaces in order to make products more modular (e.g. Baldwin and Clark, 2000; Baldwin 2008). But what happens when changes made to an existing interface leads to new product features? Moreover, what happens when rival firms substitute an existing 'open standard' by a proprietary (non-interoperable) standard interface between, in this case, lens and body?

In prior studies, such as the IBM 360 mainframe (Ferguson and Morris, 1993; Pugh et al., 1991; Baldwin and Clark, 2000), and DIN and RCA connector interface standards between hi-fi components such as the amp, CD player, and tuner (Langlois and Robertson 1992), physical interface standards remain open. Yet the literature on standards competitions provides examples where open standards are replaced by proprietary (non-interoperable) standards. Notable examples in software are internet browsers (Windrum, 2004), and Apple's proprietary DRM-AAC digital music standard (George and Chandak, 2006).

Our case study provides an example of a physical, open interface standard – the M42 screw thread with mechanical aperture coupling lever between lens and camera body – being replaced by proprietary bayonet lens-body interfaces with different configurations of electrical pin connectors. This strategy succeeded because consumers were attracted to a new feature that was made possible by the new interface: automated exposure (AE).

3. Interface innovation and the camera industry

The implications for competition and industry structure of technological substitution in a pre-existing interface – e.g. the replacement of a mechanical interface with an electrical interface – has not been considered in the prior mirroring literature. As discussed above, the 'ideal' modular product architecture is completely decomposable. It comprises a set of distinct, independent modules, and there are no dependencies between the modules (Simon 1962). In this idealised case, an interface ensures interoperability between modules but does not itself affect the function or the performance of the modules.

A number of hardware/ software IT products, and modular hi-fi systems come close to this ideal architecture. However, there are products that are not completely decomposable, i.e. in which interfaces do affect the functioning and the performance of modules. In case of cameras, an electric interface between lens and body can carry more information than a purely mechanical interface, and this made it possible to offer new product features without changing the overall product architecture or introducing new modules. If the new features facilitated by interface innovation are attractive to consumers, then a radical change in leadership and industry structure can occur.

One way of viewing AE is as a simple control system; one that uses information from the exposure meter to coordinate of a set of pre-existing components within the lens (i.e. the lens blades) and the body (i.e. the shutter). Control systems are a particular class of innovation that is relatively understudied. Notable exceptions are Sosa et al. (2003, 2004) and Lee and Berente (2012).

Sosa et al. (2003) introduced the notion of 'integral architectures', which they distinguish from modular architectures in the following way; "modular systems as those whose design interfaces with other systems are clustered among a few physically adjacent systems, whereas integrative systems are those whose design interfaces span all or most of the systems that comprise the product due to their physically distributed or functionally integrative nature throughout the product." (Sosa et al. 2003,p.p. 240-241). They apply their concept to a case study of the Pratt & Whitney PW4098 large commercial aircraft engine (Sosa et al. 2003, 2004).

The early shutter-priority and aperture-priority AE cameras were not integrative systems, nor were they more integrative in their lens-body interface than the previous generation of manual cameras. Rather, the early camera 'automation' devices required (in addition to an electrical interface) relatively minor mechanical modifications to the pre-existing shutter control and pre-existing aperture control mechanisms used in manual cameras (section 6 below). All of the other components and their functions in the lens and camera body remained the same as in manual cameras.

It is illustrative to compare this with another major innovative camera product of the late 1960s, the Polaroid's SX-70 camera (Garud and Munir 2008). That design was aimed at a different sub-market - the occasional amateur user. It was a simple to use point-and-shoot camera, light and portable, and could produce 'instant images'. The ability to produce printed images required the development of a new product architecture. Unlike AE, it radically reconfigured the existing SLR design. To start with, a new type of film cartridge was developed that contained the chemicals needed to develop a set of 10 colour positive photographs in ambient light. This obviated the need to load and remove a 35m negative film cartridge (a common source of user error), and made pictures 'instant' as there was no need to send negatives away to be developed and printed onto colour positive paper. Another notable change was that the SX-70 had a simple fixed lens, which could not be changed. Finally, to insure against power loss due to battery wear, the battery was removed from the camera body to the film cartridge. With each new cartridge there came a new battery to operate SX-70's shutter, mirrors, film advance system and flash sequencer (Olshaker 1978). Whilst the film and battery remained separate components, and the extent of their interdependence was not substantially greater than before, the nature of their interdependence had changed materially.

As well as this being a less modular design than the SLR camera, there was a change in organizational modularity for this product. Implementing the innovation required intense boundary-spanning collaboration between Polaroid and key suppliers, such as Kodak for the new film technology. Polaroid ultimately found it necessary to become a more vertically integrated firm, and develop its own in-house film competences, because of problems in achieving necessary quantity and quality of film from its main supplier, Kodak.

The introduction of simple mechanical AE on SLR cameras did not involve, or require, a radical change in product architecture. Furthermore, the degree of product modularity did not change notably. In contrast to Christensen's (2002) discussion of module integration, the lens and body modules remained completely separate. Any firm that knows the interface specification can supply either. For example, a firm can make a lens body that accepts Nikon lenses, or else make lenses that work with a Nikon body.

A key reason why Japanese firms maintained modularity and used a relatively simple, mechanical set-up for AE, is that professional photographers (then, as now) want to be able to switch instantly back to fully manual mode, when circumstances require (see section 6 below for a detailed discussion).

The professional sub-market became more vertically integrated (less organizationally modular), as it did for the amateur Polaroid sub-market, but the driver of change was very different. In the professional camera sub-market, change was due to innovating firms successfully capturing what had previously been a single, open standard for the lens-body interface. There emerged a limited number of proprietary interface standards, each controlled by a different manufacturer. The key innovators of AE who pushed these proprietary interface standards were vertically integrated entrants from Japan. The resulting competition drove out specialist European and U.S. body manufacturers. This case study counters the proposition that modular production networks are particularly advantageous in industries where there is rapid technological change (cf. Langlois and Robertson, 1992). AE was to be the first in a series of innovations that eventually transformed cameras from a manually operated product to the highly automated, computer-controlled product that we see today.

Our proposed explanation of the change in industry structure differs from prior accounts by historians such as Lewis (1991), Nelson (1998), Nakaoka et al. (2001), Alexander (2002), and Donzé (2011, 2014). These writers have highlighted the introduction of mass manufacturing techniques, applied to precision engineering products, by Japanese firms, which gave them a cost advantage over established high-end European and U.S. firms.

At the outset of the post-war era, the camera industry was dominated by separate European and U.S. specialist lens and specialist body producers.[2] The key technical challenge facing camera body specialists was the manufacture of accurate shutter speeds, and the challenge facing lens specialists was the precision grounding of glass lenses. This industry structure was consistent with the mirroring hypothesis.

High-end German and Swiss camera manufacturers used artisan 'kleinserien-produktion' in which small batches were produced with skilled labour.[3] Hitherto, mass production had only been applied to the production of simple, inexpensive cameras in the USA, most notably by Kodak.

Mass precision manufacturing may well have enabled Japanese firms to quickly catch-up to the quality of European and U.S. specialists but, we propose, it was interface innovation that facilitated the development of new product features that led to their dominance in the high-end, professional camera market. AE was the first of these novel product innovations. Following its success, Japanese firms pioneered further novel automation features, such as autofocusing, automated zoom lenses, and complex

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[2] A notable exception was Leica, which made 35mm rangefinder camera bodies and its own lenses (Fuhrman 1988).

[3] See Radkau (1989), Homburg (1991) and Abelshauser (1998, 2005) on the system of artisan 'kleinserien-produktion' extensively found in German and Swiss manufacturing developed from the late 19th century onwards and how this differs to Fordist mass manufacturing (Hounshell 1984; Scranton 2007).

multi-zone metering. All of these were predicated on the more effective electrical control of the lens-body interface.

Where integrated Japanese firms were willing, and able, to invest in the R&D required for AE, European lens and body specialists failed to coordinate a response. Reasons for technological hold-up lay on both sides. Leading camera body specialists in Germany and elsewhere had built their success on mechanical engineering. They did not develop quickly enough the capabilities required to match their Japanese rivals. Specialist lens manufacturers were equally slow to develop AE capabilities. These firms were further disadvantaged by the fact that, rather than there being a single, open electrical interface standard, there were a set of rival, non-interoperable interface standards.[4]

Integrated Japanese firms such as Nikon, Canon, Minolta and Pentax each has its own interface arrangement of electrical communication pins for lens and body. It was not economic for specialist lens producers to reverse engineer and provide compatible third-party lenses for all of the rival interfaces. Even where lens specialists focused on one of the AE options, photographers who purchased third party lenses frequently encountered compatibility issues because the specialist lens firm did not have access to the lens/body communication specifications of the Japanese standards setter. Another common problem was backwards compatibility between older third party lenses and newer bodies with incremental updates on the proprietary standard.

Industry specialisation thus proved to be the Achilles heel of German lens and body manufacturers who were unable to develop a coordinated response to the development

[4] See Farrell and Saloner 1989 for a discussion of coordination problems faced by agents wishing to switch from one standard to another.

of camera-lens automation by new Japanese firms. German firms declined in the professional sub-market and also in the amateur sub-market. In 1964, the value of global exports of all camera types by Japanese firms stood at 15 billion yen, slightly larger than that of West German firms at 14 billion yen. German exports remained flat through to 1974, rising to just 21 billion yen, while Japanese exports increased by over 500% to 92 billion yen (Nelson 1998).

4. Exposure and the artistic choice of the photographer

In order to understand the attractiveness of AE to the user, it is necessary to appreciate the issues involved in correctly exposing a piece of light sensitive film, and the artistic choices involved in selecting particular lens apertures and shutter speeds.

The combination of lens aperture (f-stop) and shutter speed (measured in seconds) determine the amount of light that passes through the camera and on to a piece of light sensitive film (or a sensor on a modern digital camera). Given the light sensitivity of the film (its ISO), and the amount of light being reflected from the subject that one is wishing to capture on the image, there will be a number of combinations of f-stop lens aperture and shutter speed that ensure a correctly exposed image i.e. an image that is not too bright (overexposed) or too dark (underexposed). In images which are overexposed and underexposed, a lot of the information and contrast that makes a good image worth viewing is lost.

A light meter measures the level of the light, and indicates an 'exposure value' (EV) at a particular ISO. Suppose the combination of film ISO and light gives an exposure value of EV11.

Table 1 indicates the set of combinations of numerical camera settings of shutter speed and f-stop which produce a set of equivalent exposure settings. F is the f-stop number of the lens aperture, and T is the shutter speed. So, for example, the combination of a large lens aperture of f/2 and fast shutter speed of 1/500 of a second, lets through an equivalent amount of light as the combination of a small lens aperture of f/22 and a slow shutter speed of 1/4 of a second.

Insert Table 1 Here

The relationship between F and T is $EV = log_2 F/T$. Rearranging, 2EV = F2/T so EV is an exponent power of two. Stops of shutter speed affect exposure in powers of two. F/stops are numbered incrementing by the square root of 2, then each squared number is a power of two.

A set of artistic choices are involved when selecting one of these combinations of aperture and shutter speed. The aperture of the lens (*N*) affects the depth of field of the image. For example, a picture taken at a wide aperture, such as f/2, will have a shallow depth of field. This is a useful choice when taking portraits, as a shallow depth of field means the features of the subject (the person) are sharp and the background is soft and blurred (this is known as bokeh). This isolates the subject from the background, ensuring the viewer's eye focuses on the features of the person.

The landscape photographer makes a very different choice. She/he wants all subjects within their image to be in sharp focus. Hence, they will select a small aperture, such as f/11 or f/16, to ensure a large depth of field. The downside of this is the relatively slow shutter speeds involved (1/15 second at f/11, and 1/8 second at f/16 for EV11). As indicated in Figure 1, any moving object within the image is liable to be blurred.

Capturing a relatively fast moving subject – such as a ball moving through the air or a bird in flight – is essential for sports and wildlife photography. Hence, the photographer must select a very fast shutter speed, such as 1/1000 second or 1/500 second. The downside of this is that they must accept, at EV11, a shallow depth of field in the image due to the need for a large aperture (e.g. f/1.4 at 1/1000 second, or f/2 at 1/500 second).

5. Benefits of AE for the professional user

Having discussed the exposure values and choices between different combinations of lens aperture and shutter speed, we can consider the advantages to the photographer of early AE systems.

With a manual camera, the photographer needs to adjust both the lens aperture via an aperture ring located on the outer body of the lens and the shutter speed via a control dial located on the camera body.

Another factor which the photographer needs to consider is changing light conditions. For example, on a partially cloudy day the light (EV values) can change rapidly as the sun periodically breaks through clouds. When this occurs, the photographer needs to adjust both lens aperture and shutter speeds in line with changing light conditions.

Compared to a manual camera, AE significantly speeds up the time to set up a photograph and significantly reduces the likelihood of an incorrectly exposed image. This is particularly attractive for press photographers, sports, and other professional photographers who must capture an image in a split instant.

Having said this, it is important for the professional photographer (then, as it is still) to be able to turn off the automated system and to manually set the aperture and shutter speed him/herself. As we shall see, the early AE systems were set up in a way that the camera modules could easily revert back to all-manual operation.

There are a number of conditions under which a user may wish to revert back to manual mode. The most common of these are low light or snow conditions, when it is more practical for the photographer to set their own exposures. Some photographers also liked to deliberately 'push' film above its native speed, deliberately underexposing the film negative and then giving it a longer development time. Others liked to 'pull' film; overexposing the negative and shortening development time.

The earliest AE cameras offered one of two alternatives of automation: 'shutter-priority' and 'aperture-priority'. With shutter-priority control, the photographer selects a shutter speed based on an artistic decision about whether to freeze or blur motion in the image. The camera contains a servo mechanism that controls the positon of the lens blades. This sets a lens aperture that is appropriate for the correct film exposure at a given EV level.

With an aperture-priority AE system, by contrast, the photographer decides on the depth of field and selects an appropriate f-stop. With this type of AE system, the camera contains a servo mechanism that controls the shutter speed. An appropriate shutter speed is automatically selected for a given EV level.

By 1974, leading Japanese manufacturers were divided into one or other camp. Canon, Konica, Miranda, Petri, Ricoh and Topcon offered shutter-priority AE, and Asahi Pentax, Chinon, Cosina, Fujica, Minolta, Nikkormat and Yashica offered aperture-priority AE.

6. Technical design of AE

In this section of the paper we critically analyse the technical design of the early AE systems. The analysis helps to clarify AE as an example of a new product feature (service characteristic) facilitated by innovation on a pre-existing interface as opposed to an architectural product change or an integrative change. It is not, as discussed, an integrative system innovation (Sosa et al., 2003). Cameras were not integrative systems prior to the development of AE, and the early AE cameras were not more integrative in their interfaces than manual cameras. To illustrate this, we shall compare the Design Structure Matrix (DSM) of a manual SLR camera with the Design Structure Matrices of aperture-priority and shutter-priority AE SLRs. The addition of new design variables (and their dependencies) are shown in red and eliminated design variables in grey.

Figure 1 presents a DSM (Steward, 1981) listing the key technical variables of a manual SLR camera, and the technical dependencies between those key variables. For example, the size of the aperture diaphragm regulates the amount of light that passes through a lens, affecting the film's exposure. The aperture blades (row 3) are mechanically controlled by an aperture ring on the outside on the lens case (row 1). The aperture ring has a set of f-stop markings. By adjusting the aperture ring, the user mechanically adjusts the position of the aperture blades and, hence, the size of aperture diaphragm.

Insert Figure 1 Here

Of particular note is the through-the-lens (TTL) exposure metering feature offered by manual SLR cameras (row 18). As discussed above, this is a distinguishing feature of the SLR design compared to twin lens reflex (TLR) cameras. The exposure metering feature has a number of dependencies.

Light passing through the lens strikes a CdS photocell (row 16), changing its conductivity, affecting the flow of electricity from a battery (row 15). This current caused an ammeter coil to rotate, deflecting a needle within an exposure meter readout (row 18). This meter readout indicates whether a particular combination of lens aperture and shutter speed will produce the correct exposure for a film ISO (preset by the user – row 17), or will otherwise produce an under- or overexposed image (see the example EV11 Table 1 above). The photographer would manually adjust the lens aperture and/or shutter speed until the correct exposure is indicated.

AE systems make use of this TTL metering system. The very first AE SLRs were shutter-priority cameras, and were entirely mechanical. When the user pressed the shutter release, a trapping blade pinned the metering needle in position. Other mechanical devices, then communicated the relative position of the trapped needle to the lens, where a servo mechanism set the lens diaphragm to the correct aperture. This servo mechanism overrides the lens aperture that had been set by the user via the lens ring.

The subsequent generation of cameras introduced microchips to control many of these functions. One of the problems of purely mechanical parts is wear and tear, leading to inaccuracies in exposure over time. The basic principles, however, remain the same. For example, with aperture-priority AE, the user selects the lens aperture via the lens ring. This information is passed to the controlling microcircuit as electrical inputs through variable resistors. A light reading from a photocell generates an electric current in response to the amount of light passing through the lens diaphragm. This is the basis for the timing of the shutter. Shutter speeds can be continually variable.

Figures 2 and 3 are DSMs for aperture-priority and shutter-priority AE camera designs respectively. Variables that differ to those of the manual camera (Figure 1) are highlighted in red, as are any differences between the interactions between key variables.

Insert Figures 2 and 3 Here

From these figures we see that early AE is *not* an integrative system, nor does it make the SLR design more integrative in its modules. The one mechanical interface between the lens and camera body has been replaced with an electrical interface that is able to carry more information.

As noted in the previous section, the set–up of the early AE designs were simple and easily allowed for the user to revert back to 'manual mode'. The mechanical AE designs either added an additional servo mechanism to control the shutter mechanism (Figure 2), or else a servo mechanism to control the lens aperture (Figure 3).

In the aperture-priority AE camera (Figure 2), the photographer sets the f-stop on the aperture ring (row 1) based on his/her artistic decision regarding the depth of field. Using EV information provided by the exposure meter (row 11, column 18), a servo mechanism controls the focal plane shutter (row 13, column 11). This automatically adjusts the shutter speed to achieve a correct exposure for the user-selected lens aperture. This mechanical servo control for the shutter (row 11) is the one, new mechanical component not present in a manual SLR (Figure 1).

Turning to the shutter-priority AE camera design (Figure 3), the one component that is new is a mechanical servo to control the aperture of the aperture blades (row 2).

Here the photographer sets the shutter speed (row 10) based on his/her artistic decision regarding the freezing or blurring of motion. Once again, EV information provided by the exposure meter readout (is used, but this time it is an input for a servo mechanism that controls the lens blades (row 2, column 18).

The one other key change that occurred, in both AE designs, was the replacement of the previously universal M42 screw thread interface standard between lens and body (row 7, Figure 1) with a bayonet-mount interface that included electrical pin connectors (row 7, Figures 2 and 3).

These connectors ensure that information passes between the lens and the camera body. A bayonet mount is needed in order to ensure that the (male) pins on the lens match exactly with corresponding (female) receptors on the camera body. In an aperture-priority AE camera (Figure 2), information from the lens aperture (set by the photographer) is carried to the exposure meter readout. In a shutter-priority AE camera (Figure 3), information from the exposure meter readout is carried to the servo mechanism controlling the lens blades.

The above matrices help us clarify the key arguments made in this paper. Firstly, the matrices help to clarify AE as an example of a new product feature due to interface innovation. The pre-existing components of the shutter mechanism and the lens aperture were adapted. There was not an architectural change to the manual SLR design. Additionally, AE is different to integrative systems discussed by Sosa el al. (2003, 2004).

In principle, a single configuration of male and female connectors could have provided a common, universal standard for all lens and body manufacturers. However, as previously discussed, Japanese firms such as Canon, Minolta, Nikon, and Pentax chose to introduce their own pin configurations. What is more, they introduced their own, proprietary bayonet mount shapes. This meant that lenses from one firm could not be attached to the camera body of another, e.g. Nikon lenses could not be attached to a Canon body, and vice versa. This forced consumers to choose lens and body combinations from a single firm.

This strategically altered the nature of competition in the professional camera subsector, from an open interface standard (M42) with which any make of lens could be used on any make of camera, to a contemporaneous standards battle where consumers were forced to choose between the lens/body combinations of rival companies.

As discussed in section 2, the winners of this standards battle were the vertically integrated Japanese start-ups who could forge ahead with AE thanks to in-house capabilities in both lens and body manufacture. The losers were the previously successful specialists who produced either lenses or camera bodies. This shift in competitive advantage within the industry adversely affected the fortunes of Japanese specialists as much as it did European and U.S. specialists. The following Section discusses the hypotheses that will be tested to examine the importance of product innovation on the industry structure.

7. Hypotheses

There are two 'pure' innovation strategies that a firm can use to move towards the quality/price efficiency frontier. The first pure strategy is to develop a process innovation which increases the efficiency of manufacturing giving the firm a cost/price advantage. The second pure strategy is to produce a camera with higher quality product characteristics. Ceteris paribus, this will tend to cost more to manufacture, and so the firm will need to charge a high price to cover the additional costs.

As noted, Lewis (1991), Nakaoka et al. (2001), Alexander (2002), and Donzé (2014) have suggested that the development of mass precision manufacturing from the 1950s onwards enabled Japanese entrants to manufacture cameras with competitive price/quality characteristics to European and U.S. firms. In this case, one would expect to find Japanese cameras at the quality/price efficiency frontier, from 1955 to 1974, across all four camera types (35mm SLR, medium format TLR, medium format SLR and medium format Hasselblad-type cameras).

The proposition forwarded in this paper is that the introduction of AE, a radical product innovation, drove the industry dynamics in two high-end, professional camera formats (35mm SLR and medium format TLR cameras). If this is the case, one would expect to see a different pattern in the DEA estimates between camera types. In the 35mm SLR and TLR camera types where AE was introduced, we would expect to see an increasing number of integrated firms located at the efficiency frontier from 1961 onwards. By contrast, in the medium format SLRs and medium format Hasselblad-type cameras where AE was not introduced, one would expect to continue to see separate specialist firms at the efficiency frontier throughout the 1955 to 1974 period.

This provides us with three testable hypotheses,

> **H1**. *In medium format SLRs and medium format Hasselblad-type cameras, models with an efficiency score = 1 are produced by specialist body manufacturers from 1955 – 1974.*
>
> **H2**. *In 35mm SLR and medium format TLR cameras, models with an efficiency score = 1 are produced by specialist firms in the 1955 – 1960 period.*
>
> **H3**. *In 35mm SLR and medium format TLR cameras, models with an efficiency score = 1 are produced by integrated firms in the 1961 – 1974 period.*

8. Dataset and methods

8.1 Data

Our dataset is collected from information published in the UK consumer magazine *Amateur Photographer*. This is a well-known, reputable, and publicly available source for contemporary secondary data. Each year, *Amateur Photographer* produced an annual 'Buyers Guide' listing makes, models, recommended retail prices, and features. Data was taken from the guides published from 1955 to 1974 inclusive.

Our dataset comprises four camera types which were used by professional photographers in this period: 35mm SLRs, medium format SLRs, medium format TLRs, and medium format Hasselblad-type cameras (Time-Life 1970; Hicks 1986; Langford 1987).[5] Of these formats, 35mm SLRs also became popular amongst amateurs from the mid-1970s onwards. We therefore analyse data for the period 1955 to 1974. The first issue of the Guide was 1955. The first model with AE that is listed in our dataset is a Japanese 35mm SLR camera, released in 1961. We use the cut-off point of 1974 because up to this point AE systems were introduced on higher priced cameras, aimed at professional users. After 1974, AE became increasingly prevalent on SLRs aimed at the amateur user, such as the Pentax ME (introduced in 1976) and the ME Super (introduced 1979) which was the largest selling SLR of all time. This is consistent with other industries in which R&D costs are recouped by first offering novel features in higher priced versions of a product (Baumol 2010).

[5] Camera types not used by professional photographers are excluded from the sample. These include box camera, folding camera, 126 and 110 cartridge, and non-reflex 35mm and medium format, and half-frame cameras.

As a data source, *Amateur Photographer* offers a number of advantages. First, the data is consistent and complete. Second, the use of an independent, publicly available source enables other researchers to access the same information to replicate results. Third, the magazine reports price and the performance features which manufacturers use to convey to the consumer the quality of their product designs and which consumers use in their decision-making.

Our dataset contains 1,816 different listings for 635 distinct camera models. Each model tends to be present in more than one year. Also, manufacturers often offered consumers different lens options. Bundles with faster lenses were more expensive. Hence, we have 1,816 complete listings for *price* and seven characteristic variables *lens speed*, *shutter speed*, *interchangeable lenses (IL)*, *internal metering*, *electronic shutter*, *automatic exposure*, and *built-in motor*. These characteristics were found to be important quality indicators in studies of the amateur camera sub-market by Alexander (2002), Windrum (2005), and Donzé (2014). The dataset also contains discrete variable information on country of origin, manufacturer's name, and camera type.

The variable *price* is the manufacturers recommended retail price and is reported in UK pounds sterling. All model prices are deflated using the official UK deflator, with 1974 as the base period. The variable *shutter speed* is the number of stops offered on the camera body. Each stop is a halving/doubling of light exposure onto the film. *lens speed* is a continuous variable containing information on the speed of the standard lens that is sold with the camera body. This is the *f* value of the lens at open aperture. Five product characteristics are dichotomous variables. *AE* takes a value of 1 if the camera model had an AE system (whether shutter-priority or aperture-priority) and a value of 0 otherwise; *IL* takes a value of 1 if the model allows for interchangeable lenses, and a value of 0 if there is a fixed lens; *internal metering* takes a value of 1 if the camera body has in-built exposure metering and 0 otherwise; *built-in motor* takes a value of 1 if the camera came with a motor for automatically winding on film between shots and 0 otherwise; and *electronic shutter* takes a value of 1 if the focal plane shutter in the camera body is electronically controlled and a value of 0 if it is mechanically controlled.

The four camera types in our dataset differ in their degree of modularity. At one end of the spectrum is the TLR camera type originally invented by Rollei. These typically had non-interchangeable lenses. At the other end of the spectrum, the Hasselblad camera type is the most modular of designs ever invented, with interchangeable viewfinders, film magazines, and lenses.

8.2 DEA model

In this paper we use non-parametric Data Envelopment Analysis (DEA) to identify the most efficient camera models over the sample period. The advantage of DEA is that one can include, within the same analysis, the effects of process innovations that affect productivity as well as product innovations that improve the quality of product features.

The technique used in this paper is the same as Farrell's (1957) non-parametric technique for measuring productive efficiency except that here there are multiple outputs (product characteristics) and one input (price). Prior applications of DEA to the measurement of product competitiveness using price as the only input and product characteristics as the outputs include Swann (1987) for fridges and fridge-freezers, Doyle and Green (1991) for computer printers, and Fernandez-Castro and Smith (2002) for cars. Applied in this way, the technique compares competing products across a number of different characteristics and identifies the most efficient products. A decision-making unit (DMU) is measured by its relative distance to the efficient frontier which is constructed from observations of comparable units. In the context of modelling cameras, the DMUs are the individual camera models. The closer the camera model to the frontier, the better the camera will be since it will provide more product characteristics for a given price. An efficient camera model will operate at a point on the frontier and receive an efficiency score of 1. A score below 1 indicates that the camera model is operating below the frontier and hence, is inefficient relative to comparable units. In the context of our data, the linear programming model is configured so as to determine how much the price could contract if used efficiently in order to achieve the same level of product characteristics. The efficiency score therefore becomes a measure of how competitively the product is priced given the product characteristics. DEA is particularly useful in that it can accommodate multiple input-output situations whilst still yielding a single measure of relative performance. Moreover, this methodology does not require an *a priori* specification of the weights assigned to the inputs and outputs. We estimate a variable returns to scale (VRS) DEA, allowing for increasing and decreasing returns (see Appendix).

DEA has a number of advantages over parametric hedonic regression. There is a tradition of estimating an average price function (of a particular form) to price and quality data and, following Cowling and Rayner (1970) measuring the competitiveness of rival products in terms of the hedonic regression residuals. There are a number of recognised limitations with this estimation method (Chow 1967; Griliches 1971; Swann and Taghavi 1992; Pakes 2003). First, whilst a product may be competitive relative to the average, it may never be bought because it is uncompetitive relative to its closest rival. The rational consumer would choose the most efficient or competitive product. Second, the estimated hedonic price function is an envelope of diverse firm cost functions and consumer indifference curves, reflecting more the diversity of agents than the functional form of individual curves (Swann and Taghavi 1992, p.16).

Non-parametric DEA for measuring efficiency is preferred to parametric Stochastic Frontier Analysis (SFA) since the latter requires one to assume a functional form for the input-output relationship. The DEA approach allows the shape of the frontier to be responsive to product innovations. In addition, the competitiveness of a particular product is assessed by reference to the immediately neighbouring products in terms of their product specification, rather than the whole market, as summarised in the parametric function.

9. Results

9.1 *Descriptive statistics*

The summary statistics for the period averages of the variables used in the estimation are given in Table 2.

Insert Table 2 Here

As noted, we have 635 different camera models over the entire sample period. These tend to be present in more than one year, with different lens bundles offered at different prices. Hence, we have a total of 1,816 observations on our set of *price* and the seven characteristic variables *lens*, *shutter speed*, *electronic shutter*, *automatic exposure*, *interchangeable lens*, *internal metering* and *built-in motor*. Table 3 shows the number of camera models in each model type.

Insert Table 3 Here

The 635 cameras originated from 15 different countries. Table 4 shows the total number of camera listings in our dataset (i.e. all body/lens bundles offered over multiple years) by country of origin. As can be seen, the largest number of camera models originated from West Germany and Japan.

Insert Table 4 Here

The average time between a camera being first being listed and eventually being removed from the listings is approximately 2 years and 11 months. The median period is 2 years. For cameras featuring *AE*, the median period is 4 years. There is a significant amount of entry and exit of camera models over the period 1955 - 1974. In 1955, 52 cameras are listed. In 1974, this number had increased to 117 listed cameras. The total number of new models introduced between 1955 and 1974 was 583, of which Japan accounted for 344 and West Germany 112 new models. Hence, the total number of models that exit the sample is 518. Of the total exits, 250 are Japanese models and 121 are West German models. This higher turn-over rate is indicative of firms that are engaged in higher rates of product innovation and/or a higher rate of firm entry and exit amongst Japanese firms than amongst West German firms.

Turning to the number of manufacturers, there are 70 different manufacturers in our dataset. Table 5 reports the number of manufacturers by country of origin. The largest number of manufacturers is in Japan, followed by West Germany. On average, a firm manufactures 23 different cameras over the 20 year period. The median number of cameras is 20.

Insert Table 5 Here

Over the period 1955 – 1974, 61 new manufacturers enter the market. Of this number, 41 are Japanese. Conversely, 46 manufacturers exit the market over this period, of which 15 are Japanese.

Figure 4 presents the number of manufacturers by national origin in each year. It highlights the dramatic change in fortunes of West German and Japanese firms during this period. The number of West German firms rises up to 1960, reaching a peak of 17 independent firms manufacturing cameras. Thereafter the number of West German firms collapses until, by 1974, there are just 4 remaining surviving firms. Japanese firms come to dominate this sub-market. There is a fall in the number of Japanese manufacturers between 1958 and 1968, from 19 to 12 firms, but the number of active Japanese firms rises thereafter.

Insert Figure 4 Here

The distribution of the number of camera models by manufacturer is listed in Table 6. The majority of manufacturers produce between 1 and 5 camera models. However, two manufacturers produce over 40 different camera models.

Insert Table 6 Here

Figure 5 shows the annual number of camera models listed from Japan, West Germany and all other countries. There is an upward trend in the number of Japanese models over time. The number of West German cameras per year is reasonably consistent up to 1965, and thereafter starts to fall year upon year. Elsewhere in the world this begins a little earlier, in 1962. The increasing share of models produced in Japan is an important indicator of the success of these firms in outperforming rivals in the professional sub-market, and is corroborated by existing data on the increasing international market shares of Japanese firms (Nelson 1998; Windrum 2005).

Insert Figure 5 Here

In order to analyse this general trend in greater detail, Figure 6 presents the annual number of camera models by country for each camera type. The number of medium format SLR and Hasselblad-type models offered each year is very small (between one and seven models per year). It is the growth in the number of 35mmm SLR models that is driving the overall trend. The number of SLR models offered by Japanese firms rose from zero in 1955 to over 80 in 1974. The number of SLR models offered by West German firms plateaued at around 20 between 1961 and 1965, after which the numbers fell year upon year.

Insert Figure 6 Here

There is a switch of production from medium format TLRs to 35mm SLR cameras over this twenty year period. The number of models offered by West German, Japanese and all other countries falls notably over the entire period. The figures for Japanese manufactured TLRs are particularly notable. In 1958 there were 21 different models manufactured in Japan. This is far larger than any other camera type that year. In 1974, just four TLRs in our dataset were Japanese. This suggests that, in order to survive, Japanese firms that began by manufacturing and exporting TLRs must have switched to the production of 35mm SLRs.

Pricing is of particular interest to the argument that mass precision manufacturing gave Japanese firms a significant cost-price advantage over European and USA. rivals. The average for West German manufacturers is £218.66, while the average for Japanese manufacturers is £185.96 (Table 1). Yet the relative average price of Japanese cameras was not consistently lower than manufacturers in other countries, or even West German firms throughout the entire period.

Consider each of the four camera types in our dataset – i.e. Medium format SLR, Hasselblad-type, medium format TLR, and 35mm SLR camera types - in Figure 7. In medium format SLR cameras, average Japanese cameras are lower than those from other countries from 1959 to 1967 but become higher thereafter. In Hasselblad type cameras they are consistently lower than West German producers of this camera type, but are not lower than from manufacturers in the 'rest of the world' (which includes Hasselblad itself). In TLRs and 35mm SLR types, the picture is similar.

These data provide mixed evidence for the proposition that mass quality manufacturing was the primary factor explaining the success of new Japanese entrants. From the mid-1960s, the trend in each of the four camera types is an upward movement in the average prices of Japanese cameras. This is consistent with a repositioning of Japanese firms as leading-edge product innovators who incur higher costs as a consequence.

Insert Figure 7 Here

We now turn to data on cameras with automatic exposure (AE). Table 7 reports, for each year, the number of new cameras that feature AE. Information is provided on the country of origin and the type of camera. 61 new cameras featuring AE (9.6% of the total) were introduced between 1955 and 1974.[6] Of this total, 56 were manufactured by a Japanese company. Just 6 models were manufactured by a West German company. It highlights the inability of West German firms to develop AE over time. No manufacturer from any other country was capable of developing AE in our sample period.

This information clearly indicates the dominance that integrated firms in Japan had over specialists (whether from Europe, Japan, or the USA.). The number of new models featuring AE increases dramatically at the end of our data period, with 10 new models featuring AE introduced in 1973 and 23 introduced in 1974.

Insert Table 7 Here

9.2 *DEA Results*

Table 8 provides data on the camera models estimated to lie on the efficiency frontier,

[6] 6% of all camera listings have *AE* (see Table 5). The difference between the two figures reflects the larger number of different lens-body combinations offered with non-AE cameras than with AE cameras.

by year, for medium format SLR, and Hasselblad-type cameras. Table 12 provides data for 35mm SLR and TLR type cameras. The two columns indicate the number of firms from each country whose models are located on the frontier. The third column indicates the number of these firms that were integrated body and lens producers. The fourth and fifth column indicate the number of cameras that feature AE and of these, the number manufactured by integrated firms.

Insert Tables 8 and 9 Here

Examining Table 9, we find strong support for Hypothesis 1. Between 1955 and 1970, the only firms producing cameras at the efficiency frontier in medium format SLR and Hasselblad-type cameras are specialist body firms. These were produced by UK, West and East German, Swedish, and Japanese body specialists. In 1971, two Japanese integrated manufacturers enter; Pentax with its 6x7 medium format SLR and Mamiya with it RB67 Hasselblad-type camera. Each remains at the efficiency frontier through to the end of the sample period. We note that both of these firms had gained experience producing other camera types used by professionals. Mamiya was an established manufacturer of TLR and 35mm SLR cameras, and Pentax of 35mm SLR cameras.

There is evidence to support Hypothesis 2 that leading edge producers of 35mm SLR and medium format TLR cameras in the pre-AE years (i.e. prior to 1961) tend to be specialist body manufacturers. 18 of the 21 cameras on the 35mm SLR frontier from 1955 to 1958 are produced by specialists. The remaining 3 cameras were produced by Zeiss Ikon, the West German integrated firm. The cameras produced by integrated Japanese firms, first appear on the SLR frontier in 1959 and 1960. Yet the majority of cameras on the frontier in these years continue to be made by specialists – 7 of the 10 cameras in 1959 and 13 of the 15 cameras in 1960.

Some integrated Japanese firms were faster in developing highly efficient TLR cameras. Still, specialist firms made the majority of TLR cameras on the efficiency frontier from 1955 to 1959.

Our findings strongly support Hypothesis 3 that the development of AE gave firms – nearly all of whom were integrated producers – a competitive advantage. Although there were relatively few 35mm SLR cameras with AE listed in our sample (Table 6), the estimated DEA VRS models indicate that many of these models are located on the efficiency frontier (Table 12). While AE on its own was not sufficient to ensure the competitiveness of a camera, the ability to offer this feature did confer a price-quality advantage.

The findings also highlight the success of integrated Japanese firms in developing competitive AE SLRs compared to specialists in other countries, and specialists in Japan. These are the leading edge cameras on which Canon, Nikon, Pentax, Minolta, and Mamiya grew to displace German and USA SLR manufacturers. There are just two 35mm SLR with AE produced by non-integrated firms. One was produced by Wirgin, a German body specialist firm, and the other was produced by the Japanese specialist Miranda.

Turning to TLR cameras, there are just two TLR cameras in the sample that feature AE (Table 6), the Rollei Magic II and the Yashica E (Heiberg 1979). Both are estimated to be at the TLR frontier during the years they are listed for sale. As previously discussed, Rollei was a specialist body producer and Yashica an integrated firm.

In order to test whether AE is a key feature, we re-estimated the SLR results while omitting AE from the equation. If the efficiency of certain Japanese cameras largely depends on the presence of AE (i.e. they are not efficient with respect to the other features) then we expect to see a very different set of cameras on the frontier if the AE variable is removed. This is indeed what we find (see Table A1 in the Appendix). A larger number of non-Japanese firms are present on the efficiency frontier when AE is omitted. This confirms that AE was a key feature affecting the price/performance competitiveness of Japanese firms in the SLR market.

10. Discussion and Conclusions

The case study provides a number of interesting insights into the link between strategic innovation and the mirroring hypothesis. With relatively minor changes to the existing camera designs, new Japanese start-ups were able to offer a new feature – AE - that was attractive to professional users. Importantly, the camera's post-innovation architecture was not substantially less modular than the pre-innovation architecture. This enabled the user to easily revert back to all-manual mode, with the camera working in exactly the same mechanical fashion as an all-mechanical camera. A market shake-out occurred as new Japanese start-ups tied access to this new feature with proprietary interface standards, forcing consumers to make a choice between rival integrated firms that could offer both lens and body combinations. This led to a 'breaking' of the mirror between the product modularity and organizational modularity as there followed a rapid change in the industry structure, from specialist to vertically integrated firms.

The emphasis on physical interfaces in this paper is in the tradition of Ulrich (1995), Ulrich and Eppinger (2008), Langlois and Robertson (1992) and Langlois (2002), and is also consistent with the notion of interface standards within the standards literature (e.g. Swann, 1987; Swann and Taghavi 1992).

There exist other definitions of interfaces and standards within the mirroring hypothesis literature. In terms of knowledge (cf. Henderson and Clark, 1990), the development of AE did not alter the underlying technological knowledge of optics and lens manufacture. Nor did it alter the underlying technological knowledge of camera body and focal plane shutter mechanics or manufacture. Moreover, the early application of AE on SLR cameras tapped into a component - through-the-lens exposure metering – that was already present on manual SLR cameras. It was not a different set of engineering and scientific principles that created difficulties for established firms, or provided the basis for the successful entry of new firms (Henderson and Clark, ibid).

An interesting question is why German lens and body specialists, who had originally developed the open M42 standard, were unable to effectively respond to new, integrated Japanese producers. There was clearly a coordination failure on the part of German producers to agree upon and coordinate a switch to a proprietary standard (cf. Farrell and Saloner 1989). This could have been one of the proprietary bayonet standards of a Japanese firm, or else their own proprietary bayonet standard.

There were two German companies with in-house body and lens capabilities who could potentially have developed a German proprietary standard - Zeiss Ikon and Leica. Zeiss Ikon was one part of the Carl Zeiss Foundation, the other being the Carl Zeiss camera lens and optical firm. The company was formed through the pre-war merger of four camera makers (Contessa-Nettel, Ernemann, Goerz and Ica), and an infusion of capital by Zeiss. Zeiss Ikon belatedly developed an SLR model with AE, the 'Contarex Electronic', which was launched in 1969. This proved too little, too late to save the company from closure in 1972.

Leica's idiosyncratic management during the 1950s meant it stayed in 35mm rangefinder production rather than moving into 35mm SLRs. When it did launch its first

SLR camera, the Leicaflex in 1964, this was deemed to be overpriced and underspecified compared to Nikon and Canon models, and more suitable for the amateur than the professional user (Schnaars 1994). As Bruno Frey, Leica's President in 1988, conceded, "Leica [hadn't] had a strategy attuned to the market … Leica just gave up the market to the Japanese" (Fuhrman 1988, p. 100).

This is sympathetic to the criticism that modular product architectures, in themselves, do not provide the information needed by different actors to coordinate activity through the market mechanism (Brusoni et al. 2001; Brusoni 2005; Hobday et al. 2005; and Brusoni and Prencipe 2006). Decisions regarding product restructuring - partition, recombine, or (in our case study) develop improved interfaces – are strategic choices. It is the visible hand of organisations driving strategy, not the invisible logic of a product architecture.

Baldwin and Clark (2000) have a still broader understanding of the relationship between thick/thin crossing points at the boundaries of modules, transaction costs between firms, and the network of organizational ties in an industry. The 'crossing point' necessary for AE was not substantially 'thicker' than that of pre-AE cameras. Our empirical findings highlight the importance of interface innovation as a key innovation strategy for developing new features while the core principles underlying the rest of the camera's functioning did not change.

The successful introduction of AE on SLR cameras was to change the direction of product innovation in the pro-innovation period. The new interface facilitated the development of further novel automation features such as autofocusing and automated zoom lenses. These are all founded on the passing of electrical information between the lens and the camera body. This raised the degree of interdependency (a thickening of the crossing point) between the lens and body modules in the post-innovation era.

As discussed, the early AE mechanisms were mechanical. Later on, successful Japanese firms began to apply electronics to their designs. These new competences enabled them to further distance themselves, in technology and in product performance, from their European and U.S. rivals.

Looking forward, interface innovation is a powerful, though typically overlooked, innovation strategy that facilitates the development of novel product features (service characteristics) in complex products. It is hoped that this paper will encourage research on interface innovation and industry structure, as well as other strategies that have led to industries in which integrated organization**s** produce modular products, or else there are modular organizations producing integrated products.

References

Abelshauser, W. 1998. "Germany: Guns, butter, and economic miracles". In: M. Harrison (ed.), *The Economics Of World War II: Six Great Powers In International Comparison*, Cambridge: Cambridge University Press, pp. 122-176.

Abelshauser, W. 2005. *The Dynamics of German Industry: Germany's Path toward the New Economy and the American Challenge.* New York: Berghahn Books.

Alexander, J.W. 2002. Nikon and the sponsorship of Japan's optical industry by the Imperial Japanese Navy, 1917-1945, *Japanese Studies*, 22 (1), 19-33.

Argyres, N.S. 1999. The impact of information technology on coordination: Evidence from the B–2 'Stealth' bomber. *Organization Science* 10: 162–180.

Baldwin, C.Y. and Clark, K.B. 2000. *Design Rules. Vol. 1: The power of modularity.* Cambridge, MA: MIT Press.

Baldwin, C.Y. 2008. Where do transactions come from? Modularity, transactions, and the boundaries of firms, *Industrial and Corporate Change* 17(1), 155–195.

Banker, R.D., Charnes, R.F. and Cooper, W.W. 1984. Some models for estimating technical and scale inefficiencies in data envelopment analysis, *Management Science* 30, 1078–1092.

Baumol, W.J. 2010. *The Microtheory of Innovative Entrepreneurship.* NJ: Princeton University Press.

Brusoni, S. 2005. The limits to specialization: Problem solving and coordination in modular networks. *Organisation Studies* 26, 1885-1907.

Brusoni, S., Prencipe, A. and Pavitt, K. 2001. Knowledge specialization, organizational coupling, and the boundaries of the firm. Why firms know more than they make? *Administrative Science Quarterly* 46, 597-621.

Brusoni, S. and Prencipe, A. 2006. Making design rules: A multidomain perspective. *Organization Science* 17(2), 179–189.

Brusoni, S. and Prencipe, A. 2011, Patterns of modularization: The dynamics of product architecture in complex systems. *European Management Review* 8: 67–80.

Cabigiosu, A. and Camuffo, A. 2012, Beyond the 'mirroring' hypothesis: Product modularity and interorganizational product and organizational modularity relations in the air conditioning industry. *Organization Science* 23: 686–703.

Cacciatori, E. and Jacobides, M.G. 2005. The dynamic limits of specialization: Vertical integration reconsidered, *Organization Studies* 26 (12), 1851–1883.

Christensen, C. M., 2002. The rules of innovation. *Technology Review* 105 (June), 33-38.

Christensen, C.M., Verlinden, M., Westerman, G., 2002. Disruption, disintegration and the dissipation of differentiability. *Industrial and Corporate Change* 11 (5), 955–993.

Chow, G. 1967. Technological change and the demand for computers, *American Economic Review* 57 (December), 1117-1130.

Colfer, L. and Baldwin C. 2016. The mirroring hypothesis: theory, evidence, and exceptions, *Industrial and Corporate Change*, 25 (5), 709–738.

Consoli, D. 2005. The dynamics of technological change in UK retail banking services: An evolutionary perspective, *Research Policy* 34, 461-480.

Cowling, K. and Rayner, A.J. 1970. Price, quality and market share, *Journal of Political Economy*, 78, 1292-1309.

Donzé, P-Y. 2011. The hybrid production system and the birth of the Japanese specialized industry: Watch production at Hattori & Co. (1900-1960), *Enterprise & Society*, 12(2), 356-397.

Donzé, P-Y. 2014. Canon catching up with Germany: The mass production of "Japanese Leica" cameras (1933-1970), *Zeitschift für Unternehmensgeschishte / Journal of Business History.* 59 (1), 27-46.

Doyle, J. and Green, R. 1991. Comparing products using data envelope analysis, *OMEGA: The International Journal of Management Science* 19(6), 631-638.

Ethiraj, S.K. 2007. Allocation of inventive effort in complex product systems. *Strategic Management Journal* 28: 563–584.

Farrell, M.J. 1957. The measurement of productive efficiency, *Journal of the Royal Statistical Society* (Series A) 20, 253-281.

Farrell, J. and Saloner, G.. 1985. Standardization compatibility and innovation. *Rand Journal* 16, 70–83.

Farrell, J. and Saloner, G. 1989. Installed base and compatibility: Innovation, product preannouncements, and predation, *American Economic Review* 76, 940-955.

Ferguson, C.H. and Morris, C.R. 1993. *Computer Wars: How the West Can Win in a Post-IBM World.* Times Books: New York, NY.

Fernandez-Castro, A. and Smith, P. 2002. 'Lancaster's characteristics approach revisited: product selection using non-parametric methods, *Managerial and Decision Economics* 23, 83-91.

Fine, C.H., Golany, B. and Naseraldin, H. 2005, Modeling tradeoffs in three-dimensional concurrent engineering: A goal programming approach. *Journal of Operations Management* 23: 389–403.

Fixson, S.K. and Park, J-K. 2008. The power of integrality: Linkages between product architecture, innovation and industry structure. *Research Policy* 37, 1296-1316.

Fuhrman, P. 1988. New focus at Leica, *Forbes* October 31 1988, 100 - 102.

Galvin, P. and Morkel, A. 2001. Modularity on industry structure: The case of the world the effect of product bicycle industry. *Industry and Innovation* 8: 31–47.

Garud, R. and Munir, K. 2008. From transaction to transformation costs: The case of Polaroid's SX-70 camera. *Research Policy* **37,** 690–705.

George, C. and Chandak, N. 2006. Issues and challenges in securing interoperability of DRM systems in the digital music market. *International Review of Law, Computers & Technology* 20 (3): 271-285.

Griliches, Z. (ed). 1971. *Price Indices and Quality Change: Studies in New Methods of Measurement.* Cambridge, MA.: Harvard University Press.

Heiberg, M. 1979. The Yashica Guide, A Modern Camera Guide Series Book, New York: Amphoto Press.

Henderson, R.M. and Clark, K.B. 1990. Architectural Innovation: The reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly* 35, 9-30.

Hicks, R.W. 1986. *Medium-format Handbook: A Guide to Rollfilm Photography.* London: Blandford.

Hobday, M., Davies, A. and Prencipe, A. 2005. Systems integration: a core capability of the modern corporation. *Industrial and Corporate Change* 14, 1109-1143.

Hoetker, G. 2006. Do modular products lead to modular organizations? *Strategic Management Journal* 27: 501–518.

Hoetker, G., Swaminathan, A. and Mitchell, W. 2007. Modularity and the impact of buyer–supplier relationships on the survival of suppliers. *Management Science* 53: 178–191.

Homburg, H. 1991. *Rationalisierung und Industriearbeit. Das Beispiel des Siemens-Konzerns Berlin 1900-1939.* Berlin: Haude & Spener.

Hounshell, D.A. 1984. *From the American System to Mass Production, 1800 – 1932*. Baltimore: John Hopkins Press.

Jacobides, M.G. 2005. Industry change through vertical disintegration: How and why markets emerged in mortgage banking. *Academy of Management Journal* 48 (3), 465–498.

Langford, M. 1987. *Michael Langford's 35mm Handbook* (1st ed.), London: Ebury Press.

Langlois, R.N. and Robertson, P.L. 1992. Networks and innovation in a modular system: Lessons from the microcomputer and the stereo component industries. *Research Policy* 21, 297-313.

Langlois, R.N. 2002. Modularity in technology and organization. *Journal of Economic Behavior and Organizations* 49, 19-37.

Langlois, R.N. 2003. The vanishing hand: The changing dynamics of industrial capitalism. *Industrial and Corporate Change* 12, 351-385.

Lee, J. and Berente, N. 2012. Digital innovation and the division of innovative labor: Digital controls in the automotive industry, *Organization Science*, 23(5), 1428–1447.

Lewis, G. (ed.). 1991. *The History of the Japanese Camera*, Rochester, NY: George Eastman House, International Museum of Photography & Film.

MacCormack, A., Baldwin, C.Y. and Rusnak, J. 2012. Exploring the duality between product and organizational architectures: A test of the "mirroring" hypothesis, *Research Policy*, 41(8), 1309–1324.

Nakaoka, T., Suzuki, J., and Miyachi, M. (eds). 2001, *Sangyo Gijutsushi*. Tokyo, Japan: Yamakawa.

Nelson, P.A. 1998. *Rivalry and Cooperation: How the Japanese Photography Industry Went*

Global. PhD Thesis, University of Warwick. Available at http://go.warwick.ac.uk/wrap/2546.

Olshaker, M. 1978. *Instant Image: Edwin Land and the Polaroid Experience.* New York: Stein and Day.

Pakes, A. 2003. A reconsideration of hedonic price indexes with an application to PC's, *American Economic Review* 93(5), 1578-1596.

Parnas, D. L. 1972. On the criteria to be used in decomposing systems into modules. *Communications of the ACM* 15(12), 1053–1058.

Pugh, E.W., Johnson, L.R. and Palmer J.H. 1991. *IBM's 360 and Early 370 systems.* MIT Press: Cambridge, MA.

Radkau, J. 1989. *Technik in Deutschland. Vom 18. Jahrhundert bis zur Gegenwart.* Frankfurt a.M.: Suhrkamp.

Ro, Y.K., Liker, J.K. and Fixson, S.K. 2007. Modularity as a strategy for supply chain coordination: The case of U.S. auto. *IEEE Transactions on Engineering Management 54*(1), 172–189.

Schilling, M.A. 2000. Towards a general modular systems theory and its application to interfirm product modularity. *Academy of Management Review* 25 (2), 312–334.

Schilling, M.A. and Steensma, H.K. 2001. The use of modular organizational forms: An industry-level analysis. *Academy of Management Journal* 44, 1149-1168.

Schnaars, S.P. 1994. *Managing Imitation Strategies: How Later Entrants Seize Markets from Pioneers.* New York: Free Press.

Scranton, P. 2007. *Endless Novelty. Speciality Production and American Industrialization, 1865 – 1925.* Princeton, NJ: Princeton University Press.

Simon, H. A. 1962. The architecture of complexity. *Proceedings of the American Philosophical Association* 106, 467–482.

Simon, H.A. 1976. *Administrative Behavior: A Study of Decision-Making Processes in Administrative Organization.* 3rd ed. New York: Free Press,

Simon, H.A. 1978. Rationality as a process and a product of thought. *American Economic Review* 68, 1-16.

Smith, D. 2009, Ch2. Types of Innovation. In: *Exploring Innovation*, McGraw Hill: London, 2nd edition, pages 38-79.

Sorkun, M. and Furlan A. 2017. Product and organizational modularity: A contingent view of the mirroring hypothesis, *European Management Review*, 14 (2), 205–224.

Sosa, M.E., Eppinger, S.D. and Rowles, C.M. 2003. Identifying modular and integrative systems and their impact on design team interactions, *Journal of Mechanical Design* 125 (June), 240-252.

Sosa, M., Eppinger, S. and Rowles, C. 2004. The misalignment of product architecture and organizational structure in complex product development. *Management Science* 50(12), 1674–1689.

Staudenmayer, N.A., Tripsas, M and Tucci, C.L. 2005. Interfirm modularity and its implications for product development. *Journal of Product Innovation Management* 22: 303–321.

Steward, D.V. 1981. The design structure system: A method for managing the design of complex systems. *IEEE Transactions on Engineering Management* 28 (3), 71-74.

Sturgeon, T.J. 2002. Modular production networks: A new American model of industrial organisation. *Industrial and Corporate Change* 11, 451-496.

Swann, G.M.P. 1987. International differences in product design and their economic significance, *Applied Economics* 19 (2), 201-213

Swann, G.M.P. and Taghavi, M. 1992. *Measuring Price and Quality Competitiveness: A Study of Eighteen British Product Markets.* Aldershot, UK: Avebury.

Takeishi, A. and Fujimoto, T. 2001. Modularisation in the auto industry: Interlinked multiple hierarchies of product, production and supplier systems. *International Journal of Automotive Technology and Management* 1: 379–396.

Time-Life, 1970, *The Camera*, New York: Time-Life Books.

Ulrich, K. 1995. The role of product architecture in the manufacturing firm. *Research Policy* 24, 419-440.

Ulrich, K. and Eppinger, S.D. 2008. *Product Design and Development.* Boston: McGraw Hill, 4th edition.

Utterback, J.M. and Abernathy, W.J. 1975. A dynamic model of product and process innovation, *Omega*, 3(6), 639-656.

Windrum, P. 2004. Leveraging technological externalities in complex technologies: Microsoft's exploitation of standards in the browser wars. *Research Policy* 33, 385-394.

Windrum, P. 2005. Heterogeneous preferences and new innovation cycles in mature industries: the amateur camera industry 1955-1974, *Industrial and Corporate Change* 14(6), 1043-1074.

Zirpoli, F. and Becker, M.C. 2011. The limits of design and engineering outsourcing: Performance integration and the unfulfilled promises of modularity. *R&D Management*, 41: 21–43.

APPENDIX

The efficiency of a selected unit k under variable returns to scale (Banker et al. 1984) can be written in the envelopment form as follows:

$$Min\ Z_k - \varepsilon\left(\sum_{r=1}^{s} S_r + \sum_{i=1}^{m} S_i\right)$$

$$Subject\ to \sum_{j=1}^{n} \lambda_j y_{rj} - S_r = y_{rk} \quad (r = 1,2, \dots, s)$$

$$and\ Z_k x_{ik} - \sum_{j=1}^{n} \lambda_j x_{ij} - S_i = 0 \quad (i = 1,2, \dots, m)$$

$$and \sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j, S_r, S_i \geq 0 \qquad Z_k\ -sign\ unbound$$

Where x_{ij} and y_{rj} are the quantities of the *i*th input and the *r*th output of the *j*th unit, and ε is a small positive number.

The above can be solved as a straightforward linear programming problem. The programme is solved for each unit in the sample and hence an efficiency score Z_k is generated for each one. A unit is termed efficient if its efficiency rating (Z_k) obtained from the DEA model is equal to one. Units that achieve an efficiency score below one (Z_k<1) are deemed inefficient. The envelopment surface obtained from this model results in a convex hull.

Figure A1 shows the constant returns to scale (CRS) and variable returns to scale (VRS) frontiers for a single input and single output system for five units labelled A to E. If CRS is assumed then the relevant frontier is a straight line ray from the origin and going through point C. C is therefore the only efficient unit since it lies on the frontier. For VRS, the frontier is formed by units A, C and E. The remaining units are classified as inefficient since they do not lie on the frontier.

Insert Figure A1 Here

Figure A2 shows the efficient frontier for a multiple input situation for the case where output is constant across DMUs that produce using two inputs. The efficiency frontier is represented by line CAD. E and B both lie above this frontier and are therefore deemed inefficient. DMU E would need to reduce its inputs to the amounts used by A if it is to be efficient.

Insert Figure A2 Here

Table 1. *Equivalent Combinations of Lens Aperture and Shutter Speed at EV11.*

Aperture

Bokeh <--> All in focus

F	f/1.4	f/2	f/2.8	f/4	f/5.6	f/8	f/11	f/16	f/22	f/32
T	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2

Shutter speed

Freeze image <--> Motion Blur

Table 2. *Summary Statistics*

	Mean	*Median*	*S.D.*	*No. observations*
price	188.61	160.37	137.36	1,816
lens speed	2.8	2.8	1.6	1,816
shutter speed	9.6	10	2.7	1,816
electronic shutter	0.02	0	0.15	1,816
automatic exposure	0.06	0	0.22	1,816
interchangeable lens	0.68	1	0.47	1,816
internal metering	0.44	0	0.49	1,816
built-in motor	0.08	0	0.27	1,816

Note: *price* is deflated by 1974 price index.

Table 3. *Number of Distinct Cameras in the Sample, By Camera Type*

Camera Type	Number of Cameras
SLR	14
Hasselblad	23
TLR	131
35mm SLR	467
Total	*635*

Table 4. *Number of Camera listings in the Sample, By Country of Origin*

Country	Number of Cameras
Japan	344
West Germany	131
East Germany	72
UK	14
US	8
Sweden	6
Hong Kong	3
China	1
France	11
Italy	5
Poland	2
Czech	6
Soviet Union	12
Monaco	1
Switzerland	19
Total	**635**

Table 5. *Number of Manufacturers in the Sample, By Country of Origin*

Country	Number of Manufacturers
Japan	32
West Germany	11
East Germany	4
UK	8
US	2
Sweden	1
Hong Kong	1
China	1
France	3
Italy	2
Poland	1
Czech	1
Soviet Union	1
Monaco	1
Switzerland	1
Total	*70*

Table 6. *Distribution of Cameras by Manufacturer, 1955 to 1974*

No. of camera models	No. of manufacturers	%
1-5	39	56
6-10	12	17
11-20	10	14
21-30	2	3
31-40	5	7
Over 40	2	3
Total	**70**	**100**

Table 7. *New Models Introduced with Automatic Exposure, by Year (1955 – 1974).*

Year	Camera Type	Country	No. of Cameras
1961	35mm SLR	Japan	2
1962	35mm SLR	Japan	1
	35mm SLR	West Germany	2
1963	35mm SLR	Japan	2
	TLR	West Germany	1
1964	35mm SLR	Japan	1
	TLR	Japan	1
1965	35mm SLR	Japan	2
1966	35mm SLR	Japan	2
1967	35mm SLR	Japan	2
1969	35mm SLR	West Germany	2
1970	35mm SLR	Japan	2
1971	35mm SLR	Japan	4
1972	35mm SLR	Japan	4
1973	35mm SLR	Japan	10
1974	35mm SLR	Japan	23

Table 8. *Number of Efficient MF-SLR, Hasselblad-Type Models by Year, Country, and Integrated Firms (VRS)*

Year	*Medium Format-SLR*			*Hasselblad-type*		
	Country	No. of Firms in each country	No. of Integrated Firms	Country	No. of Firms in each country	No. of Integrated Firms
1955	UK	1	0	-	-	-
1956	UK	1	0	Sweden	1	0
1957	UK	1	0	Sweden	1	0
1958	UK	1	0	Sweden Japan	1 1	0 0
1959	UK	1	0	Japan	1	0
1960	UK Japan	1 1	0 0	Sweden Japan	1 1	0 0
1961	UK Japan	2 1	0 0	Japan	2	0
1962	UK Japan E. Germany	1 2 1	0 0 0	Japan	2	0
1963	Japan E. Germany	1 1	0 0	Japan	2	0
1964	Japan E. Germany	1 1	0 0	Japan	2	0
1965	E. Germany	1	0	Sweden Japan	1 2	0 0

1966	E. Germany	1	0	Sweden	1	0
				Japan	2	0
1967	E. Germany	1	0	Sweden	1	0
				Japan	3	0
				W. Germany	1	0
1968	E. Germany	1	0	Japan	1	0
				W. Germany	1	0
1969	E. Germany	1	0	Japan	2	0
				W. Germany	1	0
1970	E. Germany	1	0	Japan	2	0
				W. Germany	1	0
1971	E. Germany	1	0	Japan	3	1
	Japan	1	1	W. Germany	1	0
				Sweden	1	0
1972	E. Germany	1	0	Japan	3	1
	Japan	1	1	W. Germany	1	0
				Sweden	1	0
1973	E. Germany	1	0	Japan	3	1
	Japan	1	1	W. Germany	1	0
				Sweden	1	0
1974	Japan	2	1	Japan	2	1
				Sweden	1	0

Table 9. *Number of Efficient TLR, 35mm SLR Models by Year, Country, AE, and Integrated Firm (VRS)*

				TLR					***35mm-SLR***	
Year	**Country**	**Total No. of Firms**	**No. of Integrated Firms**	**No. of AE Cameras**	**No. of AE Cameras by Integrated Firms**	**Country**	**Total No. of Firms**	**No. of Integrated Firms**	**No. of AE Cameras**	**No. of AE Cameras by Integrated Firms**
1955	W. Germany	2	1	0	0	E. Germany	4	0	0	0
	UK	1	0	0	0	W. Germany	3	1	0	0
1956	W. Germany	3	0	0	0	E. Germany	2	0	0	0
	USA	1	0	0	0	W. Germany	2	1	0	0
	UK	1	0	0	0	Switzerland	1	0	0	0
						Italy	1	0	0	0
1957	W. Germany	2	0	0	0	E. Germany	2	0	0	0
	USA	1	0	0	0	Italy	1	0	0	0
	UK	1	0	0	0					
1958	W. Germany	1	0	0	0	E. Germany	2	0	0	0
	USA	1	0	0	0	W. Germany	2	2	2	2
	Japan	3	2	0	0	Switzerland	1	0	0	0
	UK	1	0	0	0					
1959	France	1	0	0	0	E. Germany	4	0	0	0
	USA	1	0	0	0	W. Germany	3	1	0	0
	Japan	3	2	0	0	Japan	2	2	0	0
						Switzerland	1	0	0	0
1960	W. Germany	1	0	0	0	E. Germany	4	0	0	0
	USA	1	0	0	0	W. Germany	8	1	0	0
	Japan	4	4	0	0	Japan	2	2	0	0
						France	1	0	0	0

1961	France	1	0	0	0	E. Germany	3	0	0	0
	USA	1	0	0	0	W. Germany	3	0	0	0
	Japan	3	3	0	0	Japan	4	4	2	2
						France	1	0	0	0
1962	W. Germany	3	0	0	0	E. Germany	4	0	0	0
	France	1	0	0	0	W. Germany	4	0	1	0
	Japan	4	4	0	0	Japan	3	3	2	2
						France	1	0	0	0
1963	W. Germany	3	0	0	0	E. Germany	3	0	0	0
	Japan	4	4	0	0	W. Germany	3	0	1	0
						Japan	7	7	3	3
1964	W. Germany	3	0	1	0	E. Germany	2	0	0	0
	Japan	4	4	1	1	W. Germany	2	0	0	0
						Japan	7	7	3	3
1965	W. Germany	3	0	1	0	E. Germany	3	0	0	0
	Japan	4	4	1	1	W. Germany	2	0	0	0
						Japan	11	9	4	3
1966	W. Germany	3	0	1	0	E. Germany	3	0	0	0
	Japan	3	3	0	0	W. Germany	2	0	0	0
						Japan	7	6	4	3
1967	W. Germany	3	0	1	0	E. Germany	3	0	0	0
	Japan	4	3	0	0	W. Germany	1	0	0	0
						Japan	13	12	4	3
1968	W. Germany	1	0	0	0	E. Germany	4	0	0	0
	Japan	4	4	0	0	Japan	8	8	4	4
1969	W. Germany	1	0	0	0	E. Germany	3	0	0	0
	Japan	4	4	0	0	W. Germany	1	1	1	1
						Japan	7	7	3	3

1970	W. Germany	1	0	0	0	E. Germany	3	0	0	0
	Japan	4	4	0	0	W. Germany	1	1	1	1
						Japan	8	8	4	4
1971	W. Germany	1	0	0	0	E. Germany	1	1	1	1
	Japan	3	3	0	0	W. Germany	1	1	1	1
						Japan	8	7	5	4
1972	W. Germany	1	0	0	0	E. Germany	2	0	0	0
	Japan	3	3	0	0	W. Germany	1	1	1	1
						Japan	10	10	5	4
1973	W. Germany	1	0	0	0	E. Germany	2	2	2	2
	Japan	3	3	0	0	W. Germany	1	1	1	1
						Japan	9	9	5	5
1974	W. Germany	1	0	0	0	E. Germany	2	2	2	2
	Japan	3	3	0	0	W. Germany	1	1	1	1
						Japan	12	12	7	7

Figure 1. *Manual SLR Design Structure Matrix*

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	Aperture ring (user control)	.																						
2	Servo control (aperture blades)																							
3	Aperture blades	X		.																				
4	Optics size				.																			
5	Lens casing diameter X				X	.																		
6	Lens weight			X	X		.																	
7	M42 screw thread interface							.																
8	Lever reset								.															
9	Interior dark sealing (box)									.														
10	User control (shutter speed)										.													
11	Servo control (shutter speed)																							
12	Shutter release button												.											
13	Focal plane shutter										X		X	.										
14	Film wind mechanism														.									
15	Battery															.								
16	CdS photocell															X	.							
17	ISO Dial																	.						
18	Exposure meter															X	X	X	.					
19	Reflex mirror																			.				
20	Pentaprism																				.			
21	Viewfinder/Focusing screen																			X	X	.		
22	Body Size												X	X	X	X				X	X	X	.	
23	Body Weight												X	X	X	X				X	X	X	X	.

Figure 2. *Aperture-Priority SLR Design Structure Matrix*

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	Aperture ring (user control)	.																						
2	Servo control (aperture blades)																							
3	Aperture blades	X		.																				
4	Optics size				.																			
5	Lens casing diameter X				X	.																		
6	Lens weight			X	X		.																	
7	**M42 screw thread interface**							.																
8	Lever reset																							
9	Interior dark sealing (box)									.														
10	User control (shutter speed)										.													
11	**Servo control (shutter speed)**											.							X					
12	Shutter release button												.											
13	Focal plane shutter											X	X	.										
14	Film wind mechanism														.									
15	Battery															.								
16	CdS photocell															X	.							
17	ISO Dial																	.						
18	Exposure meter							X								X	X	X	.					
19	Reflex mirror																			.				
20	Pentaprism																				.			
21	Viewfinder/Focusing screen																			X	X	.		
22	Body Size												X	X	X	X				X	X	X	.	
23	Body Weight												X	X	X	X				X	X	X	X	.

Figure 3. *Shutter-Priority SLR Design Structure Matrix*

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	Aperture ring (user control)	.																						
2	Servo control (aperture blades)		.																X					
3	Aperture blades	X	X	.																				
4	Optics size				.																			
5	Lens casing diameter X				X	.																		
6	Lens weight			X	X		.																	
7	M42 screw thread interface							.																
8	Lever reset																							
9	Interior dark sealing (box)									.														
10	User control (shutter speed)										.													
11	Servo control (shutter speed)																							
12	Shutter release button												.											
13	Focal plane shutter										X		X	.										
14	Film wind mechanism														.									
15	Battery															.								
16	CdS photocell															X	.							
17	ISO Dial																	.						
18	Exposure meter															X	X	X	.					
19	Reflex mirror																			.				
20	Pentaprism																				.			
21	Viewfinder/Focusing screen																			X	X	.		
22	Body Size												X	X	X	X				X	X	X	.	
23	Body Weight												X	X	X	X				X	X	X	X	.

Figure 4. *Number of Manufacturers by Country of Origin,* 1955 to 1974

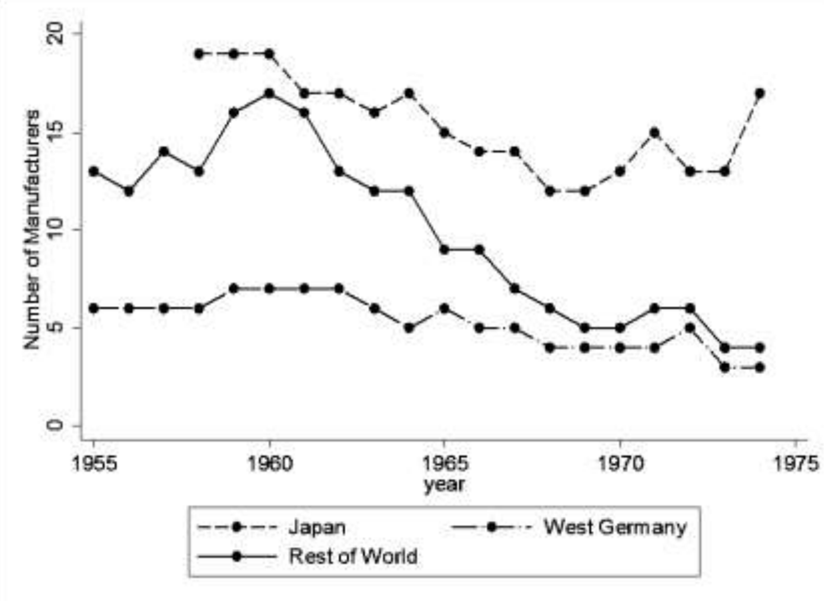


Figure 5. *Annual Number of Camera Listings from Japan, West Germany, and Rest of the World*

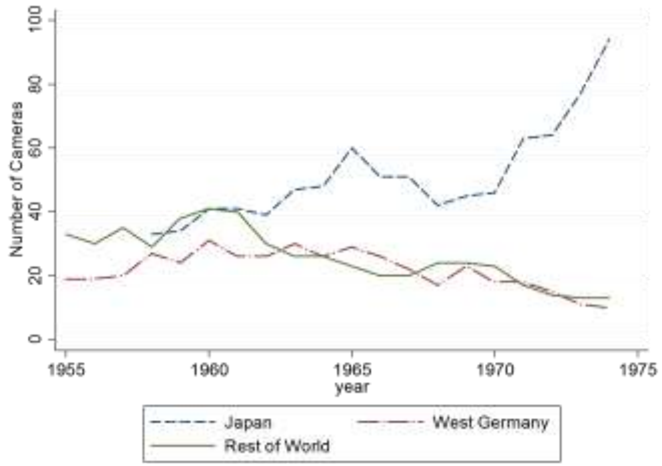


Figure 6. *Number of Camera Listings in Each Year from Japan, West Germany and Rest of the World, By Camera Type*

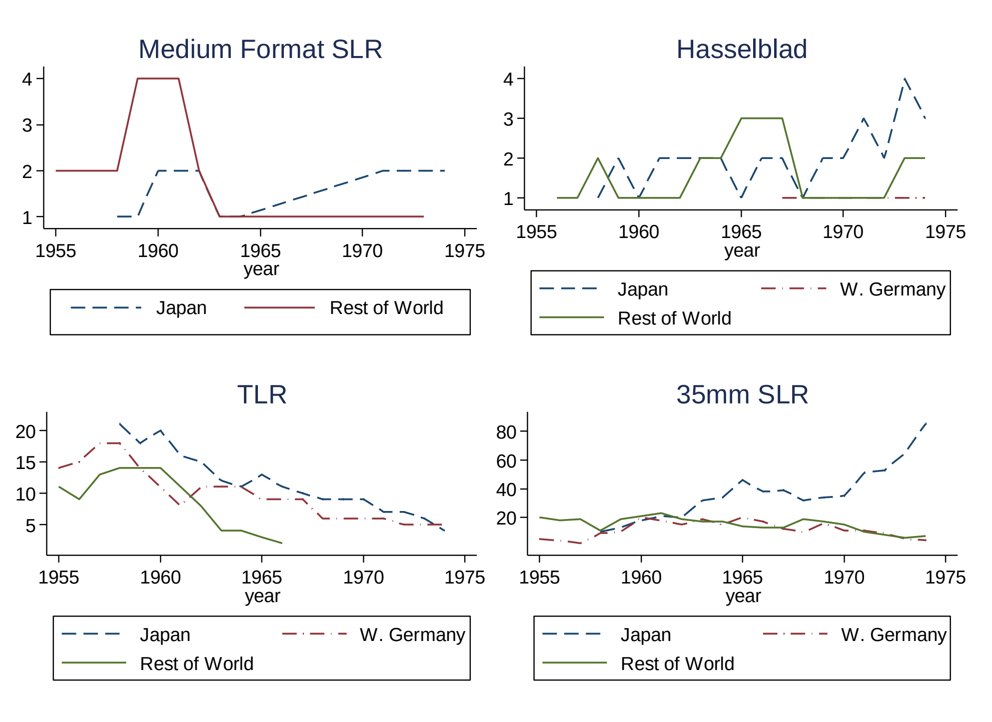
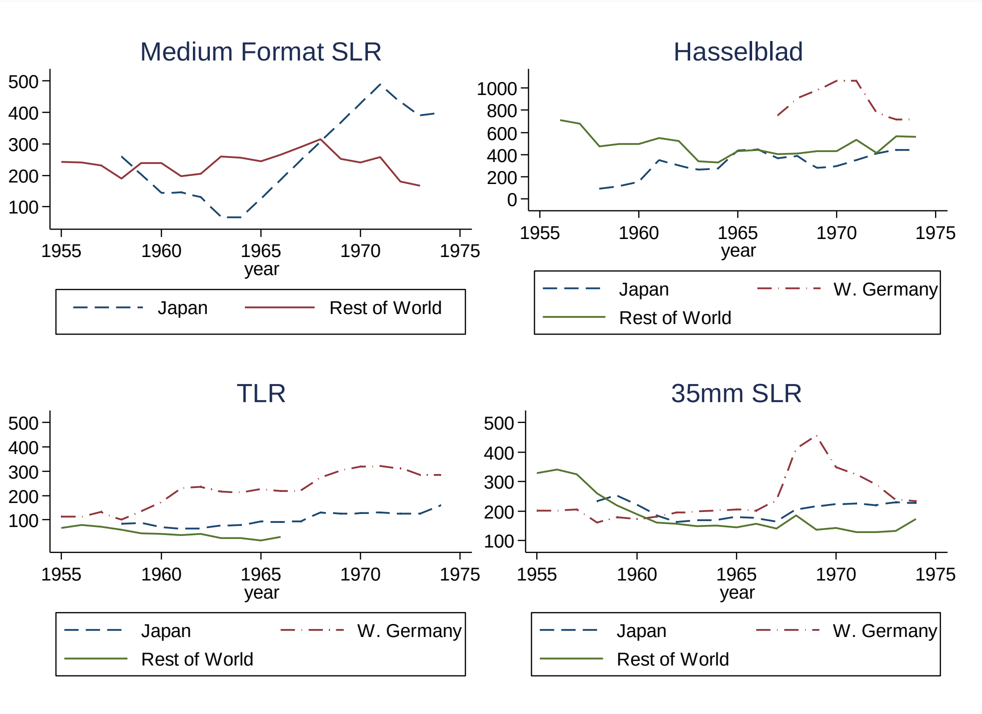


Figure 7. *Average Price of Cameras by Country of Origin, by Camera Type.*



APPENDIX

Figure A1. *CRS and VRS Efficiency Frontiers in the Single Input and Single Output Case*

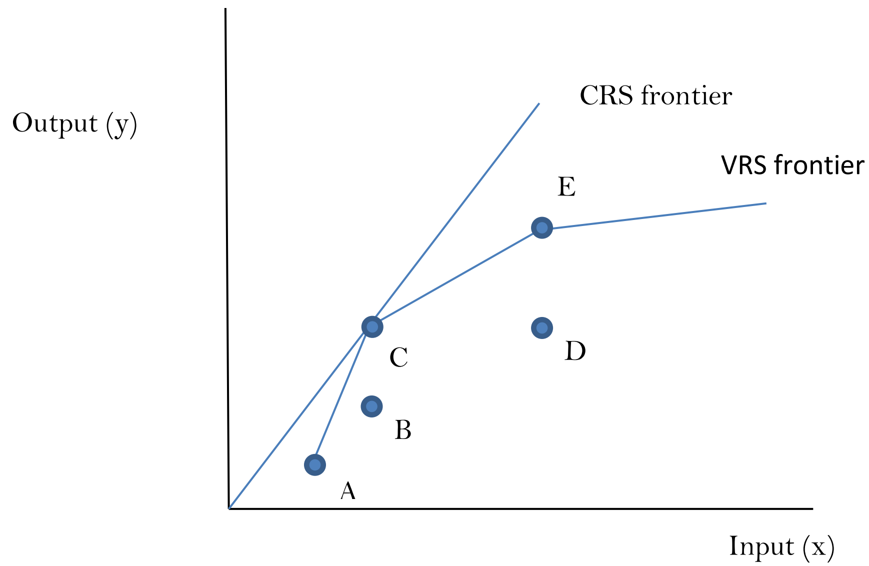


Figure A2. *DEA Frontier for DMUs that Produce a Constant Output using Two Inputs*

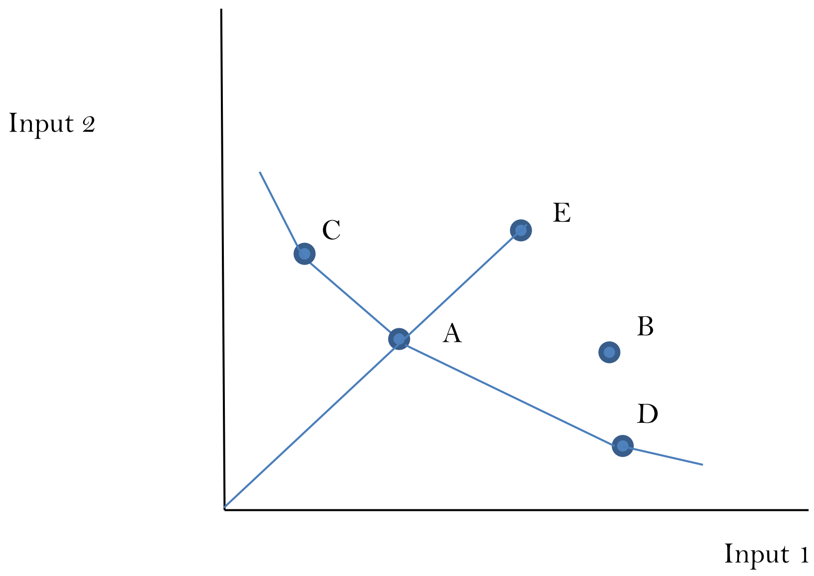

Input 2
C
E
A
B
D
Input 1

Table A1. *Number of Efficient 35mm SLR Models by Year, Country, AE, and Integrated Firm (VRS) Excluding AE Feature*

		35mm-SLR			
Year	**Country**	**Total No. of Firms**	**No. of Integrated Firms**	**No. of AE Cameras**	**No. of AE Cameras by Integrated Firms**
1955	E. Germany	4	0	0	0
	W. Germany	3	1	0	0
1956	E. Germany	2	0	0	0
	W. Germany	2	1	0	0
	Switzerland	1	0	0	0
	Italy	1	0	0	0
1957	E. Germany	2	0	0	0
	Italy	1	0	0	0
1958	E. Germany	2	0	0	0
	W. Germany	2	2	2	2
	Switzerland	1	0	0	0
1959	E. Germany	4	0	0	0
	W. Germany	3	1	0	0
	Japan	2	2	0	0
	Switzerland	1	0	0	0
1960	E. Germany	4	0	0	0
	W. Germany	8	1	0	0
	Japan	2	2	0	0
	France	1	0	0	0
1961	E. Germany	4	0	0	0
	W. Germany	4	0	0	0

	Japan	2	2	0	0
	France	1	0	0	0
1962	E. Germany	4	0	0	0
	W. Germany	3	0	0	0
	Japan	1	1	0	0
	France	1	0	0	0
1963	E. Germany	5	0	0	0
	W. Germany	2	0	0	0
	Japan	4	4	0	0
1964	E. Germany	5	0	0	0
	W. Germany	2	0	0	0
	Japan	4	4	0	0
1965	E. Germany	3	0	0	0
	W. Germany	2	0	0	0
	Japan	7	7	0	0
1966	E. Germany	3	0	0	0
	W. Germany	2	0	0	0
	Japan	4	4	1	1
1967	E. Germany	4	0	0	0
	W. Germany	1	0	0	0
	Japan	10	10	1	1
1968	E. Germany	4	0	0	0
	Japan	5	5	1	1

1969	E. Germany	4	0	0	0
	W. Germany	1	1	1	1
	Japan	5	5	1	1
1970	E. Germany	3	0	1	0
	W. Germany	1	1	1	1
	Japan	5	5	2	2
1971	E. Germany	1	0	0	0
	W. Germany	1	1	1	1
	Japan	8	8	3	3
1972	E. Germany	3	0	0	0
	W. Germany	2	1	1	1
	Japan	6	6	1	1
1973	E. Germany	2	0	0	0
	W. Germany	1	0	0	0
	Japan	7	7	3	3
1974	E. Germany	2	0	0	0
	W. Germany	1	0	0	0
	Japan	8	8	3	3