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Resource reallocation across successive systemic innovations: How Rolls-Royce shaped the evolution of the turbojet, turboprop, and turbofan

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Abstract

Research Summary: Despite the importance of *resource reallocation* in shaping a variety of strategic outcomes, strategy scholars have paid only limited attention to the processes by which firms reallocate their resources across successive *systemic innovations*. To explore these processes, we conducted an in-depth historical case study on *Rolls-Royce*'s role in three distinct systemic innovations that marked the transition from piston engines to jet engines in the civil aviation industry: the turbojet, the turboprop, and the turbofan. The analysis helps explain how and why Rolls-Royce's central role stemmed from its ability to reallocate existing non-scale free organizational and technical resources. A key finding of this study is the identification of the *horizontal transfer* of functional modules as a critical process, especially during the incipient phase of a systemic innovation. The analysis also highlights the role that specific organizational arrangements, particularly a firm's *integrative capabilities*, have in shaping the effectiveness with which resources are reallocated.

Managerial Summary: Focusing on resource reallocation is important to understand why some firms effectively reallocate their resources through successive systemic innovations while others cannot, even if they have similar resources and face the same environmental conditions. By delving into the technological aspects of aeroengine development and exploring why Rolls-Royce had the capabilities to successfully integrate key functional modules across various modular levels, we clarify the relationship between technology and organization that underlies resource reallocation—a topic that has received only scant attention in the strategy literature.

KEYWORDS

horizontal transfer, integrative capability, resource reallocation, Rolls-Royce, systemic innovation

1 | INTRODUCTION

Firms regularly are confronted with the need to reallocate their resources to different uses in the face of changing environmental conditions, such as the advent of innovations that systemically impact their industry. Despite the importance of *resource reallocation* in shaping a variety of strategic outcomes (e.g., Amore & Mastrogiorgio, 2022; Bower, 1970; Burgelman, 1983; Cattani, 2005, 2006; Coen & Maritan, 2011; Helfat & Maritan, 2024; Levinthal & Wu, 2024; Maritan & Lee, 2017), strategy scholars have paid only limited attention to the processes through which firms reallocate their resources across *systemic innovations*, and the organizational arrangements and capabilities involved. Focusing on such processes, arrangements, and capabilities is important to understand why some firms effectively reallocate their resources while others cannot, even if they have similar resources and face the same environmental conditions.

To fill this gap, we conducted an in-depth historical case study to examine the role played by *Rolls-Royce* in three distinct systemic innovations that marked the transition from piston to jet engines in the civil aeroengine industry—that is, the turbojet, the turboprop, and the turbofan. After reviewing key events in the history of aeroengines, we drew on Carignani et al.'s (2019) model of technological evolution to explore the extent to which Rolls-Royce's ability to innovate in each systemic innovation stemmed from its resource reallocation decisions and the type of resources involved. One key insight of this model is the identification of the *horizontal transfer* of functional modules (defined below) as a critical evolutionary process during the incipient phase of a systemic innovation.[1] Our case study sheds important light on the specific processes by which resources can be reallocated, as well as the organizational arrangements and capabilities that support those processes. Thus, our study resonates with recent calls for

[1]The model builds on Woese's (2002, 2004) model of (cell) evolution that explicitly incorporates horizontal transfer of genes—alongside vertical inheritance—as a key mechanism driving evolution in biology.

more research on how resources are reallocated across application domains and the "structures and processes by which these diverse activities are managed" (Levinthal & Wu, 2024, p. 2).

We contribute to the resource reallocation literature in several ways. First, we elaborate a historically grounded evolutionary perspective on resource reallocation. In particular, we study resource reallocation across successive systemic innovations (the turbojet, turboprop, and turbofan) that profoundly shaped not just the aeroengine industry, but the entire aviation industry.[2] The use of an in-depth historical case study is more suitable than other methodological approaches (Argyres et al., 2019; Hargadon & Douglas, 2001), especially if the goal is to gain insight into the fine-grained processes by which a firm (here, Rolls-Royce) reallocates its resources, the reasons behind its reallocation decisions, and the contextual conditions in which such decisions were made. The historical perspective (Jones & Zeitlin, 2008) is also central to the work of strategy scholars who, like Chandler (1962) and Penrose (1959), have made seminal contributions to research on resource reallocation. Second, examining Rolls-Royce's resource reallocation over time exposes the evolutionary origins of successive systemic innovations, showing how and why those innovations arose from the reallocation of organizational and technical resources that to a large extent were available inside the firm (Levinthal & Wu, 2024). Finally, the case analysis reveals how specific organizational arrangements and dynamic *integrative capabilities* (Helfat & Campo-Rembado, 2016; Henderson, 1994; Iansiti & Clark, 1994) critically shape how effectively resources are reallocated. By probing the technological aspects of aeroengine development and exploring why Rolls-Royce had the capabilities to successfully integrate key functional modules across various modular levels, we further elucidate the relationship between technology and organization (Baldwin, 2023; Baldwin & Clark, 2000; Sanchez & Mahoney, 1996) that underlies resource reallocation—a topic that, with few exceptions (Helfat & Maritan, 2024; Levinthal & Wu, 2024), has received only scant attention in the strategy literature.

The rest of the paper is organized as follows. We first briefly review relevant background literature that conceptualizes resource reallocation as a dynamic integrative capability. Next, we expose the study's research design and the methodological approach used in the case analysis. We then present the basic taxonomy of aeroengines examined in the paper and a summary description of their main functional modules, followed by a history of key events leading to the turbojet, turboprop, and turbofan. After discussing the main findings and theoretical implications of our study for resource reallocation, we conclude by outlining directions for future research.

2 | BACKGROUND

2.1 | Resource reallocation as a dynamic integrative capability

We define *reallocation* as the partial or complete transfer of resources from one use to another within a firm, such as when a team of engineers is pulled away from one project to work on a

[2]*Systemic* innovations correspond to what Henderson and Clark (1990) define as *radical* and *architectural* innovations. As we shall see, systemic innovations typically require the alignment and coordinated adjustment across different stages in a vertical chain (Teece, 1996) due to systemic interdependencies that necessitate the architectural reconfiguration of functional modules (see also Prencipe, 2000).

different one.[3] The ability to effectively *reallocate* resources is part of the more general ability of a firm to *allocate* resources, which has been extensively discussed in prior work (see, in particular, Helfat & Maritan, 2024). The process by which resources are reallocated is also at the heart of the resource *redeployment* literature, which has examined the intertemporal scope economies (Helfat & Eisenhardt, 2004) that firms can achieve by redeploying non-scale free resources (Levinthal & Wu, 2010) across different application domains or between units in multi-business firms, as well as the financial implications (e.g., Giarratana et al., 2021; Sakhartov & Folta, 2014, 2015) and the opportunity cost (Levinthal & Wu, 2024) of such resource redeployment efforts.

Firms can reconfigure their resource positions through several managerial interventions, from investments in new resources to the *reallocation* of existing resources. However, not all firms are equally capable of reallocating their existing resources (Cattani, 2005), even if they possess similar resources or face the same environmental conditions. In other words, some firms have the ability to reallocate their resources more effectively than others. It is therefore important to examine the underlying *processes*—what Teece et al. (1997) call "dynamic capabilities"—to understand how and why firms differ in reallocating resources over time. While a systematic review of the literature on dynamic capabilities goes beyond the scope of this article (for a review, see Dosi et al., 2000; Schilke et al., 2018), both the capability to reallocate resources and the underlying processes (Coen & Maritan, 2011) are key to explaining why some firms are consistently innovative (Eisenhardt & Martin, 2000; Pisano, 2017). Of particular interest here is the role of integrative capabilities, namely those dynamic capabilities that enable vertically integrated firms "to adapt to and create a continuing stream of innovations" (Helfat & Campo-Rembado, 2016, p. 249). It is thanks to these integrative capabilities that firms can effectively coordinate the different functional activities typically involved in designing and developing new technologies (Helfat & Raubitschek, 2000, 2018; Henderson, 1994; Iansiti & Clark, 1994).[4] In industries experiencing subsequent systemic innovations, vertically integrated firms with integrative capabilities are more likely to develop systemic innovations than more specialized firms. Integrative capabilities "might in some circumstances help integrated firms adapt to systemic technological change that is competence destroying within and/or across stages of production" (Helfat & Campo-Rembado, 2016, p. 259). However, the specific processes that underlie these capabilities—especially those that involve the reallocation of resources (the focus of this article)—are rarely studied.

Building on previous research that conceptualizes an artifact—for example, a technology—(Arthur, 2009; Basalla, 1988) as consisting of different "functional modules" (Ulrich, 1995), Carignani et al. (2019) recently emphasized the critical role of the *horizontal* transfer of existing functional modules in eliciting systemic innovation. Serving as building blocks of a specific technological artifact, these modules can be transferred horizontally and repurposed across

[3]For instance, during a phase of systemic innovation impacting the industry and the survival chances of the firm.

[4]Early formulations of the notion of integrative capabilities refer to "skill in internal integration, such as the capacity for coordination, leadership and organizational routines that ensure efficient communication between organizational subunits" (Iansiti & Clark, 1994, pp. 565-566); or "the ability to exchange information across boundaries within the firm" (Henderson, 1994, p. 610); or the knowledge of "how to integrate, different activities, capabilities, and products within a vertical chain or across vertical chains" (Helfat & Raubitschek, 2000, p. 964). The notion proposed by Helfat and Campo-Rembado (2016) both builds upon and extends these early formulations by providing more specificity about the constitutive elements of integrative capabilities; moreover, it does not refer only to innovation but has broader applications (e.g., diversification into new businesses).

distinct technological trajectories (Dosi, 1982).[5] Horizontally transferred functional modules can foster the emergence of a completely new technological artifact (e.g., an aeroengine) built around these modules. This is possible because a functional module embodies not only the knowledge required to replicate a specific technological component (e.g., a compressor or a turbine), but also the specialized human capital, tools, machines, testing and production facilities, and engineering culture that enable a firm to design, prototype, manufacture, and integrate functional modules into a new architecture (Baldwin & Clark, 2000; Carignani et al., 2019; Colfer & Baldwin, 2016).[6]

This notion of functional module is consistent with the concept of *module* in the modularity literature, whereby a module transcends the physical object (e.g., a technological component) to include the knowledge and the "technical recipe" embedded in this object (Baldwin, 2020). The modularity literature also suggests that most technological artifacts are modular, and this modular structure in turn shapes how other resources (e.g., engineers from different organizational units or specialized machineries and tools, among others) are reallocated to replicate key components and integrate them into a new artifact. Examining the horizontal transfer of functional modules sheds light on the processes by which functional modules—and the *resources* embedded in them—are reallocated and then integrated into larger systems. These processes lie at the core of "modular" systemic innovations (Baldwin, 2023; Baldwin & Clark, 2000; Sanchez & Mahoney, 1996; Simon, 1962)—that is, innovations that establish "a new dominant design and, hence, a new set of core design concepts embodied in components that are linked together in a new architecture" (Henderson & Clark, 1990, p. 11).[7]

To gain deeper insight into these processes of resource reallocation, we conducted an in-depth historical case study of Rolls-Royce's role in shaping the evolution of the aeroengine industry by investigating three successive systemic innovations in which Rolls-Royce played a key role: the turbojet (including the centrifugal turbojet, the shared origin of the three innovations), the turboprop, and the turbofan.

3 | RESEARCH DESIGN AND METHODS

Following an established research tradition for studying how firms respond to technological and market changes (Cattani et al., 2017; Chai, 2017; Danneels, 2011; David et al., 2013; Hargadon & Douglas, 2001), we adopted a historical approach to examine how the interplay between firm-level inventive efforts and contextual factors shaped the process of resource reallocation. This method is well-suited to analyzing rare events that, like the introduction of systemic innovations (Helfat & Campo-Rembado, 2016), usually display complex dynamics and

[5]By analogy, the functional modules of a technological artifact correspond to what evolutionary biologists call "a discrete entity whose function is separable from those of other modules" (Hartwell et al., 1999, C47-C48). A functional module also can be conceptualized as a *replicator*—the technological (and cultural) analogue of a genotype—which is defined as the entity that "passes on its structure directly in replication" (Hull, 1980, p. 318).

[6]The concepts of "functional module" and "technological component" are distinct. While the latter refers strictly to a physical component, the former encompasses not only the technological component itself but also the knowledge and other resources required to replicate and integrate that component into a complex artifact.

[7]However, the "partitioning of activities into those that can take place independent of one another" (Helfat & Campo-Rembado, 2016, p. 253) pertains to a more mature stage of development, when the interfaces among modules are defined and, therefore, the production and even design of some of them can be outsourced. Given our focus on the early generative phase of a systemic innovation, "modularity" as a means of coordination does not apply.

context-specific meanings. It provides the distance required to study how the interaction between main actors and contextual forces unfolds over time (Argyres et al., 2019; Hargadon & Wadhwani, 2023; Kieser, 1994), thus shedding light on the complexity of managerial choices related to resource reallocation. The same information would not be possible "to capture in a large-scale quantitative empirical study" (Maritan & Lee, 2017, p. 2145; see also Bower, 2017). Consistent with historically oriented research, our narrative aims to illustrate, sharpen, and ground our theoretical agenda rather than provide an empirical test (de Jong et al., 2015).

Accordingly, we conducted an in-depth historical case study of Rolls-Royce's role in three successive systemic innovations that marked the transition from piston engines to jet engines (turbojet, turboprop, and turbofan) in the aeroengine industry. To appreciate its role in each of these systemic innovations—and how the process of reallocating resources unfolded over time—it is important to place them in the context of the revolution in the aeroengine industry that began in the troubled peacetime of the late 1930s, grew during World War II, and continued into the postwar civil aviation period (Brusoni & Prencipe, 2001). These developments took place over a period of several years and involved different nations (United Kingdom, Germany, United States, and France, among others) and firms (Rolls-Royce, General Electric, Pratt & Whitney, Power Jets, Heinkel, and other players, including large incumbents that did not survive), and their larger industrial context.

Against this backdrop, the success of Rolls-Royce in managing the transition was not entirely obvious. At the time, Rolls-Royce had an extraordinary reputation as a manufacturer of military power plants; indeed, Rolls-Royce's Merlin aeroengine still is considered the pinnacle of the piston aeroengine. Unfortunately—to the dismay of Rolls-Royce and its early customers in the civil aviation market—the same aeroengine performed poorly when powering a civil aircraft (Pugh, 2001). Furthermore, although Rolls-Royce was regarded as the top firm for engineering sophistication in the British aeroengine industry, it had competitors with superior expertise in civil aviation. Despite this seemingly unfavorable beginning, Rolls-Royce was able to introduce a stream of systemic innovations: an improved centrifugal turbojet (the *Welland*) and the first axial turbojet (the *Avon*), the first turboprop (the *Dart*), and the first turbofans (the *Conway* and the smaller *Spey*). As our analysis reveals, at the heart of this sustained process of systemic innovation were key resource reallocation decisions made by Rolls-Royce.

To enhance the robustness of our historically grounded account, we followed Kipping and Üsdiken (2014) methodology and triangulated different types of historical sources to reduce bias and increase confidence in the empirical findings. Our historical analysis is based on aeroengine histories and archival documents; these are organized and described in the Appendix at the end of the paper, along with a summary of the three main steps of our analysis. First, we utilized key archival sources (e.g., Griffith, 1937), the availability of which was critical to understand technical details, establish the timing of key events, and examine the resource reallocation decisions that shaped the invention of the turbojet, turboprop, and turbofan. These sources allowed us to revisit events and decisions through the eyes of the people directly involved in them and identify precisely when those decisions were made, so attenuating the risk of retrospective sense-making. Some of these archival sources were purchased in book format from the Rolls-Royce Heritage Trust (Birch, 2016; Heathcote, 1992), an organization established in the early 1980s with the aim of preserving the history of Rolls-Royce by publishing a series of historical documents (many of which focus on aeroengines).[8] Second, we relied on the work

[8]We identified the key documents in the Historical and Technical Series Catalogs (updated April 2022) and obtained them by contacting the Corporate Heritage administration at Rolls-Royce Heritage Trust.

of different historians, which was essential to triangulate the data. In addition to referencing classic studies of the aeroengine industry (Boyne & Lopez, 1979; Constant, 1980; Lloyd, 1978; Schlaifer & Heron, 1950), we drew extensively on more recent studies (Decher, 2020; Giffard, 2016; Lloyd & Pugh, 2004; Pugh, 2001; Stroud, 2018). Third, we relied on several authoritative biographical books by former Rolls-Royce engineers (e.g., Harker, 1976; Hooker, 1984; McKenzie, 2001) that offer a unique perspective on Rolls-Royce's approach to innovation, its engineering culture and, in particular, the way it reallocated resources in designing, developing, and manufacturing the various types of aeroengines under consideration.[9] Finally, we had email exchanges with historians and industry experts, who not only helped us fill some gaps in the historical narrative, but also validated our analysis and interpretation of the main events. This study is retrospective and, therefore, has the advantage of the "big picture"—that is, "how things developed and the outcomes that ensued" (Van de Ven & Poole, 2002, p. 875). Although historical studies can run the risk of construct validity problems or bias, our use of multiple, distinct data sources minimizes these potential problems (see the "sources of historical evidence" table in the Appendix). Besides allowing us to identify more precisely some crucial technological antecedents and organizational factors that favored the emergence of different aeroengine types, this triangulation further mitigates the risk of retrospectively imposing meaning on historical events based on our knowledge of outcomes.

We used the historical material from these sources to further enhance our understanding of resource reallocation. The various cases of systemic innovation should therefore be viewed not merely as an illustration, but as an "inspiration for new understanding" (Cattani et al., 2017, p. 970; Siggelkow, 2007). To organize and analyze our data, the development of figures and tables was essential. In particular, Figure 1 and Figure A1 (in the Online Supplement on the journal website)[10] illustrate, respectively, the main aeroengine types and the first aeroengine within each type introduced by Rolls-Royce over the study period (from approximately the late 1930s until the early 1960s). While Figure 2 traces the evolution of these aeroengines by highlighting the transfer of the main functional modules, Figure 3 focuses on the specific resources that Rolls-Royce reallocated in order to develop a paradigmatic aeroengine: the *Welland*. Table A1 (in the Online Supplement) presents an overview of the main resources that Rolls-Royce reallocated when designing and producing each of the engines reported in Figure A1. The focus is on the key people involved and the organizational units in which design, development, and manufacturing occurred. By presenting both the key resources that were reallocated and the underlying processes, these tables and figures help illustrate the link between the data and the main theoretical constructs.

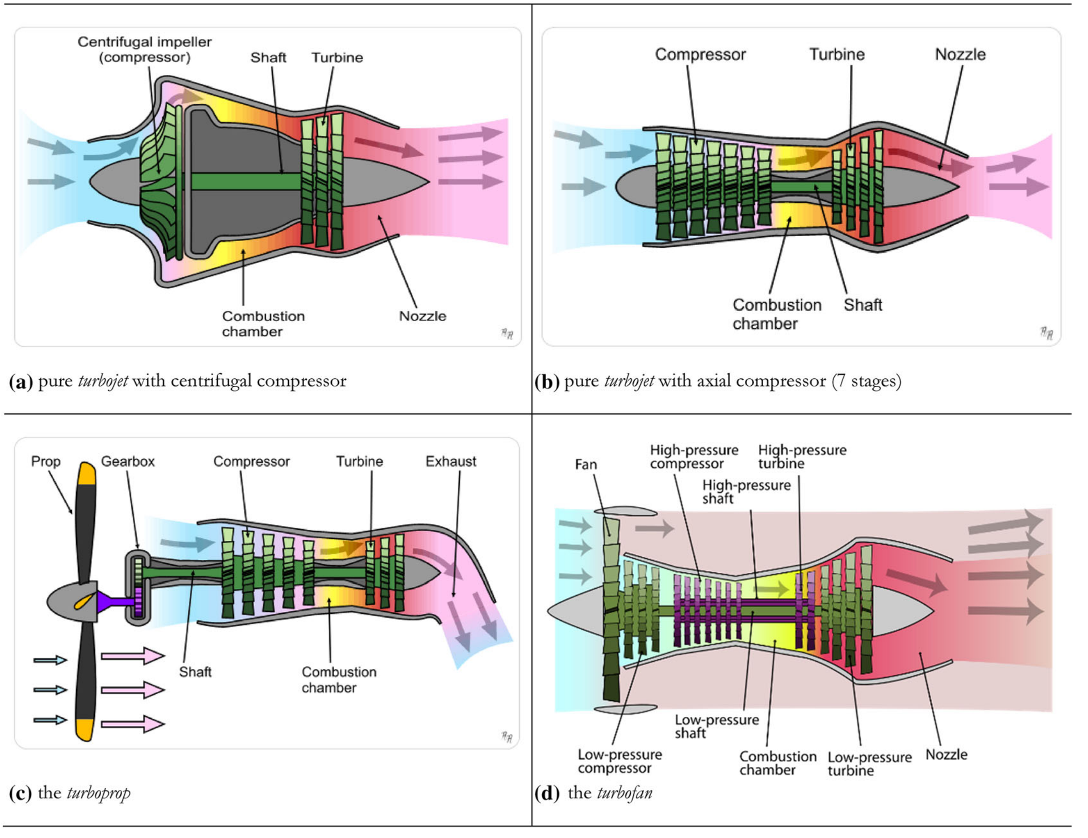
4 | CASE ANALYSIS

4.1 | Aeroengines: Basic taxonomy and functional modules

Today we are accustomed to jet engines, a dominant design that has remained unchanged for more than 60 years. Except for minor sub-segments of general aviation in which *piston*

[9]Several quotes from these materials and reported here can be considered "historical interviews" with engineers and managers involved in the design and development of the various aeroengines; as many of these people are deceased or retired, such interviews would otherwise be unobtainable. Another advantage of relying on these interviews is that "we avoid retrospective bias by using interviews published during those years" (Anthony et al., 2016, p. 168).

[10]From now on, all figures and tables in the Online Supplement will be labeled with an "A" preceding the number.



(a) pure *turbojet* with centrifugal compressor

(b) pure *turbojet* with axial compressor (7 stages)

(c) the *turboprop*

(d) the *turbofan*

FIGURE 1 Aeroengines: Modular structure, functioning principles, and a basic glossary. Source: Wikimedia. A BASIC GLOSSARY: *Combustion chamber*: A functional module of the aeroengine where the fuel is mixed with air and burned. *Turbine*: A functional module that takes power out of the exhaust stream of the aeroengine to power a compressor (or a propeller). *Compressor*: A functional module that compresses air, reducing its volume and increasing its pressure, allowing the aeroengine to burn more fuel and do more work, thus increasing its power (at high altitudes, where oxygen is less concentrated, the compressor allows the combustion to continue). *Centrifugal*: A compressor in which compression is achieved by forcing air outward—that is, centrifugally. *Axial*: A compressor in which compression is achieved by forcing air in parallel to the rotation axis, among *rotors* with increasingly small diameters and distanced by increasingly small spaces. *Stage* (*of a compressor*): A single rotor—that is, a single rotating disc composed of blades where the air impinges, being compressed to a higher pressure. Axial compressors are composed of multiple stages. Pressure is lower in outer stages (close to the air intake) and higher in inner stages (close to the combustion center). Stages also refer to rotors in the turbine. *Shaft*: A component that connects the turbine to the compressor, transferring power from the back of the aeroengine to the front. *Reverse-flow* VS *straight-through combustion chamber*: When the air enters at the back and moves forward VS when the air enters in a straight manner. *Propeller and gearbox*: In a turboprop, the turbine powers a *propeller*, and a (reduction) *gearbox* is used to convert the high rotation of the turbine into a lower rotation suited to the propeller. "Contra-rotating" propeller refers to two propellers arranged one behind the other and rotating in opposite directions. *Fan*: in a turbofan, the turbine powers a *fan*, mounted on a duct and located before the compressor. Part of the air in the duct "bypasses" the core of the aeroengine without being compressed and heated. *Nozzle*: The end of an exhaust tube of a varying cross-sectional area used to modify the flow of exhausting gas. *Source*: Giffard (2016), p. 317.

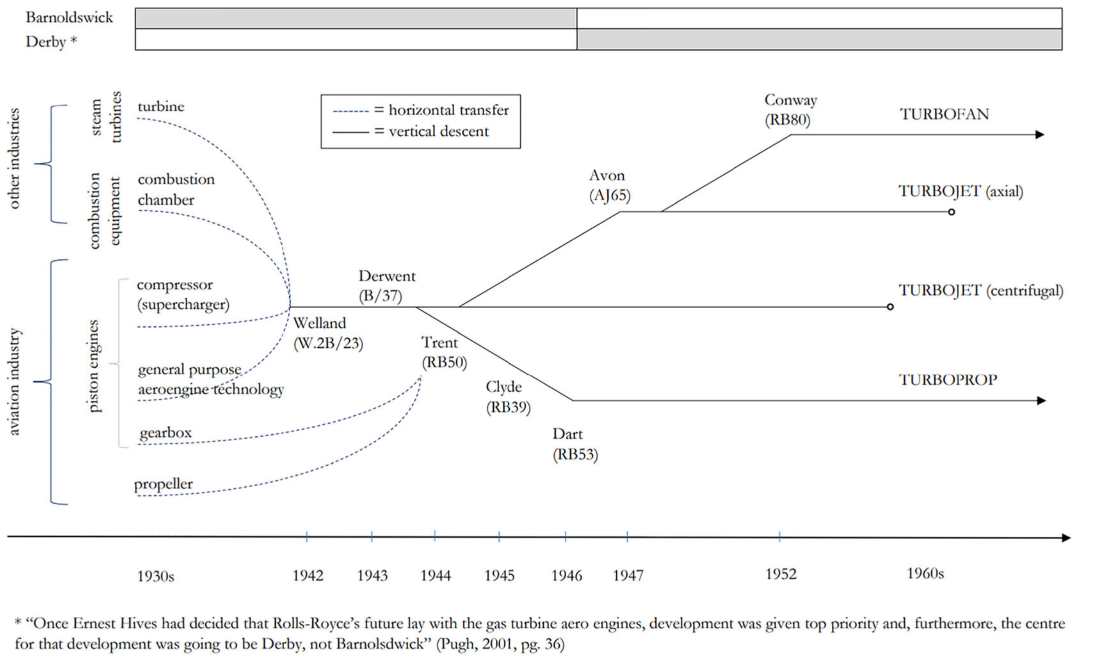


FIGURE 2 Aeroengines evolution, key functional modules and their origins. The transition between the explorative phase (dominated by horizontal transfer and architectural innovation) and the exploitative phase (dominated by vertical descent and modular innovation) coincides with what Woese calls the *Darwinian Threshold*—that is, a critical point in early biological evolution characterized by the emergence of vertical descent supplanting horizontal transfer as the main force driving evolution. After the *Darwinian Threshold*, horizontal transfer still is possible, but its importance and frequency decreases. Although Woese's hypothesis is controversial in biology, it is of interest when applied to technological evolution since technological *Darwinian Thresholds* are evident and significant in the story of several systemic innovations. In the aeroengine case, the technological *Darwinian Threshold* can be located in the introduction of the turboprop engine.

aeroengines (similar to those in most cars) are still in use (in total about 5% of the global aeroengine market), all modern aeroengines—commonly called jet engines—are based on a gas turbine fed by a turbo-compressor. According to recent data, the jet engine market was valued at 49.01 billion dollars in 2021 (65% of which was in the commercial segment), and it is projected to reach 112.6 billion dollars in 2029.[11] The three firms that lead the jet engine market are General Electric, Pratt & Whitney, and Rolls-Royce, which holds a market share of around 18%. The key jet engine types, whose designs are illustrated in Figure 1, are the following:

- The "pure" *turbojet* (panels a and b)—the jet engine type that powered the first jet aircrafts (fighters and bombers) in World War II. It later was replaced by the turbofan, which gradually became dominant after 1960, thanks to its improved propulsive efficiency and a significant decrease in noise (Saravanamuttoo, 1987).
- The *turboprop* (panel c)—which dominates military and civil transports, regional airliners, general aviation, and helicopters.[12] It covers about 25% of the global jet engine market. It is

[11]We obtained these data from Fortune Business Insights, a market research company that provides yearly reports based on trusted sources for a variety of industries. The updated report on the aeroengine industry is available online.
[12]The turboprop variant used in helicopters is called the *turboshaft*; it covers about 5% of the global jet engine market.

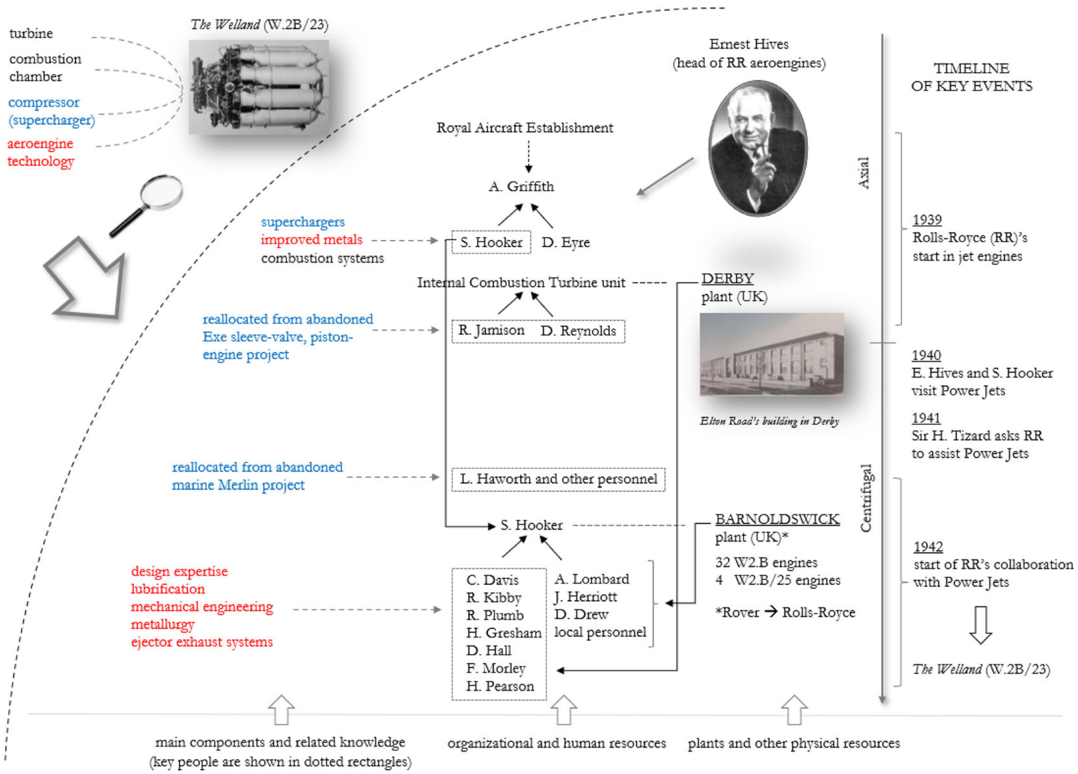


FIGURE 3 A detailed illustration of the resource allocations leading to the *Welland*. The figure is based on the historical background subsection "resource reallocation in the turbojet phase." The blue and black colors indicate the key functional modules that were transferred *horizontally*, while the red color indicates the transfer of general purpose aeroengine technology.

important to stress that the turboprop was the first dominant design in jet airliners. Its modular architecture has remained unchanged from its beginning in World War II, and it still is the most effective jet engine in terms of propulsive efficiency. In military aircrafts, the turboprop is appropriate when lower speeds combined with other performances (e.g., short take-off) are required. Following its introduction, the turboprop quickly supplanted the previous dominant design (the piston engine) in important military niches.

- The *turbofan* (panel d)—the dominant design in most combat aircrafts, long-haul airliners and transports, and executive general aviation. It covers about 65% of the global jet engine market.

All jet engines consist of several functional modules: a *compressor*, a *combustion chamber*, and a *turbine*. The turboprop aeroengine also contains a *propeller* and a *gearbox*, while the turbofan contains a *fan* (see Figure 1 and the glossary below the figure). In its simplest configuration (the "pure" *turbojet*, shown in panels a and b), a compressor-turbine rotor is kept rotating thanks to the fuel burned in the combustion chamber. When the fuel combusts, it generates gas that exits from a nozzle at high speeds, propelling the aircraft (jet propulsion). In the *turboprop* (panel c), a turbine converts all the jet-stream energy into shaft power, driving a *propeller* through a *gearbox* (propeller propulsion). In the *turbofan* (panel d), a low-pressure turbine drives a ducted *fan* (mixed fan and jet propulsion). Having clarified these essential technical concepts, we now present a stylized history of Rolls-Royce's role in shaping the evolution of the turbojet, turboprop, and turbofan—and the resource reallocation involved.

5 | HISTORICAL BACKGROUND

5.1 | The turbojet

The turbojet revolution, which began in the early 1920s, has been hailed as the most important innovation in the history of aviation since the Wright Brothers, with consequences so profound as "to be acclaimed by pundits as an 'age'" (Constant, 1980, p. 1). As military and civil aviation required bigger and faster aircrafts, the intractable limits of piston engines, which until then were the dominant design in the industry, became evident (Decher, 2020). By the late 1930s, most incumbents in the aeroengine industry and some aircraft manufacturers had reallocated considerable human and technical resources to meet the growing demand for more powerful piston aeroengines that could fly at high altitudes. To this end, they formed "turbo-supercharger"[13] divisions or created research units that conducted a significant degree of experimentation and prototyping of jet engines with the support of scientific advisors and testing facilities.

Despite these early efforts, the first jet engines capable of functioning on their own power were not created by the big players but instead by two small *inventive institutions* (Giffard, 2016)[14]: Power Jets, founded in the UK in 1936 under the guidance of Frank Whittle, a young Royal Air Force pilot and engineer; and Heinkel, a small research and prototyping unit (not the entire Heinkel Aircraft Company, which had been founded in 1922), owned by aircraft manufacturer Ernst Heinkel. In 1936, Heinkel hired Hans von Ohain, then a 25-year old physicist, to head his newly-created *Sonder-Entwicklung* (i.e., Special Development) unit to design and prototype the jet engine. The year 1937 marked a turning point when successful first runs of a "pure" turbojet were performed almost simultaneously in the United Kingdom and Germany. In the United Kingdom, the WU engine prototyped by Power Jets first ran on its own power on April 12, 1937.[15] In Germany, Heinkel's turbojet HeS1, designed by von Ohain, had undergone its first run about a month earlier (von Ohain, 1979). The new aeroengine was based on a centrifugal compressor (see the glossary below Figure 1).

At first, the turbojet faced challenges in rivaling the prevailing piston engine design (Griffith, 1937). However, the Battle of Britain in 1940 and the ensuing escalation of bombing on British and German cities during World War II demonstrated the vulnerability of high-altitude strategic bombers to fighter-interceptors. In June 1941, British Prime Minister Winston Churchill recognized the strategic need for an aeroengine that could power a new class of faster fighter-interceptors, and the pure turbojet was selected for this application (Giffard, 2016). This decision prompted a series of design efforts that soon would lead to the Gloster Meteor Mk.I (initial flight in 1943, operational in 1944)—the first British jet fighter, powered with the *Welland* aeroengine pioneered by Power Jets, but manufactured by Rolls-Royce. It is against this

[13]A specific air-compressing device "powered by a turbine located in an engine's exhaust stream, which contains useful energy that can be used to do work" (Giffard, 2016, p. 321). See also "compressor" in the glossary.

[14]By "inventive institutions," Giffard refers to companies (e.g., Power Jets) or parts of larger companies (Ernst Heinkel Flugzeugwerke) that "remain competitive through invention" and "specialize in deriving commercial advantage from novelty rather than production" (2016, p. 149).

[15]All aeroengine codes are based on appendix C in Giffard (2016). The key aeroengines of the case are also reported using their common names in *italics* (*Welland*, *Derwent*, *Trent*, *Clyde*, *Dart*, *Avon*, *Conway*).

backdrop that the key role of Rolls-Royce in the transition from the piston engine to the turbojet design—which initiated a new paradigm in aviation—needs to be examined.

5.2 | Rolls-Royce: Resource reallocation in the turbojet phase

In the late 1930s, when the turbojet revolution began, Rolls-Royce was still a major manufacturer of piston engines—including key functional modules like the turbo-compressor, which played a critical role in later developments. The Merlin piston engine, powering (among others) the famed Spitfire and Mustang fighter planes, was at the time the pinnacle of Rolls-Royce's design capabilities (Giffard, 2016). That is why the company took little interest in the first functioning jet engines and the initial critical role played by inventive institutions like Power Jets. Rolls-Royce's development program in gas turbines began in 1939 under the leadership of Ernest Hives, head of the Rolls-Royce aeroengine division. It was Hives who, in 1939, recruited Arnold Alan Griffith from the Royal Aircraft Establishment to begin work on gas turbine aeroengines at Rolls-Royce. A highly respected expert on gas turbines, Griffith had proposed an axial compressor for the turboprop aeroengine as early as 1929 (Constant, 1980). Hives instructed Griffith to continue his theoretical studies of different internal combustion turbine (ICT) and axial compressor layouts.

Griffith was assigned a personal assistant and draughtsman, Donald Eyre, whose task was to translate Griffith's elaborate schemes into practical designs for the firm's experimental shop. Hives also assigned a key figure in the development of the Merlin supercharger, Stanley Hooker (who had joined Rolls-Royce in January 1938), to work closely with Griffith when the latter arrived at Rolls-Royce. To avoid competition for resources with the Merlin piston engine, an ICT unit was formed at Derby to take over development of the CR.I—Rolls-Royce/Griffith's experimental axial compressor layout. The first two members of the new ICT unit, Robin Jamison and Douglas Reynolds, were reallocated from the canceled Exe sleeve-valve piston engine project. In June 1941, "the ICT section included four men [...] who had previously worked on piston engines" (Giffard, 2016, p. 77).[16] While the ICT unit at Derby struggled to get the axial CR.I running, Hives decided to broaden Rolls-Royce's turbojet program by including a centrifugal aeroengine. He made this decision after visiting the Power Jets factory at Lutterworth with Hooker in August 1940. Compared to the CR.I, the Power Jets WU was a "vision of simplicity": even though "it looked a very crude and outlandish piece of apparatus" (Hooker, 1984, p. 50), Hives and Hooker recognized the development potential of the Power Jets scheme. This was a critical turning point.

In May 1941, Sir Henry Tizard, chairman of the Aeronautical Research Committee, approached Hives and suggested that Derby should assist Power Jets by manufacturing certain difficult parts for the Whittle engine. This marked the start of Rolls-Royce's increasing involvement in the design and development of simpler centrifugal turbojet aeroengines, and from "this small beginning a fairly extensive degree of technical collaboration developed between Rolls-

[16] As Giffard noted, "making new machines requires *continuities* of expertise, design, and management" and "important continuities between piston engines and jet engines included engineering organizations, methods, and capital goods (along with the skill to operate them) as well as existing designs for parts belonging to other machines" (2016, p. 70, emphasis added). As shown by these examples, these continuities played a crucial role in resource reallocation.

Royce and Power Jets" (Lloyd, 1978, p. 129).[17] Whittle was enthusiastic about this arrangement and promised full collaboration from the staff of Power Jets. In fact, he had become increasingly frustrated with Rover, a car manufacturer that the government had enlisted to manage the large-scale production of the turbojet (Giffard, 2016), due to what he considered its inability to deliver production-quality parts for a test engine.

Starting in January 1942, Rolls-Royce agreed to collaborate with Power Jets as a subcontractor on the design of a new centrifugal turbojet aeroengine with a power output like that of the W.2B, also known as the *Welland* (the W.2B followed the WU, W.I and W.2). This ultimately allowed Rolls-Royce to tap into Power Jets's design experience. The joint engine was known as the WR.I (where "WR" stands for Whittle-Rolls-Royce). Hives placed Lionel Haworth, who had headed the abandoned marine Merlin project, in charge of the turbojet development. Other required personnel also were reallocated from the same project. The new aeroengine project "offered a way for Rolls-Royce to learn about centrifugal jet engines from the pioneers and translate that knowledge into firm expertise" (Giffard, 2016, p. 81). Hives insisted that Rolls-Royce be responsible for designing, developing, and manufacturing the aeroengines to allow Rolls-Royce to expand its experience with the turbojet.

Since the collaboration between Rover and Power Jets on the W.2B had become increasingly tense due to technical and personal reasons, in late 1942, the Ministry of Aircraft Production (MAP) offered Rolls-Royce the chance to manage both the large-scale production of the turbojet and the government's two jet engine factories, Barnoldswick and Clitheroe, which the government previously had assigned to Rover in 1940. In November 1942, Rover's jet factory at Barnoldswick (with its production facilities and human resources) was exchanged for Rolls-Royce's Meteor tank engine factory in Nottingham. Rover also handed over a total of 32 W.2B aeroengines and four "straight-through" W.2B/26 engines that had been developed by Adrian Lombard. Hives decided to reallocate all experimental work on jet engines to Barnoldswick, which was transformed into "an experimental and development center only" (Hooker, 1984, p. 74). In terms of resource reallocation, "*in one stroke, nearly 2,000 men and women, and massive manufacturing facilities, were focused on the task of getting the W.2B engine mechanically reliable and ready for RAF service*" (Hooker, cited in Pugh, 2001, p. 287). In January 1943, Rolls-Royce took full control of the factory at Barnoldswick. Stanley Hooker (who had joined Rolls-Royce in January 1938) was posted at Barnoldswick (where Rover's turbojet design team had moved from Clitheroe). He was put in charge of Barnoldswick's technical team, and in April of the same year, he became chief engineer. Hives gave him "more or less *carte blanche*" to choose his team, which he "modeled strictly according to the Derby format, that is, in three autonomous and separate groups, covering respectively design, mechanical development and engine performance" (Hooker, 1984, p. 79). Coming from Rolls-Royce's supercharger division, Hooker had been a key figure in the development of the Merlin supercharger and had worked closely with Griffith when the latter arrived at Rolls-Royce. His experience in the design of centrifugal superchargers, along with improved metals and combustion systems, put the engine back on track, and it soon entered production.

Some members were reallocated from Rover, where they had served in various capacities on the turbojet team: Adrian Lombard, the designer and engineer who had led Rover's design team

[17]On January 12, 1942, Hives wrote to Air Commodore Whittle to elaborate on these proposals: "I want to impress upon you that this is not put forward with the intention of competing with the Whittle; it is with the sole desire of helping the national effort. We want to look upon our contribution as an extension of your existing facilities for development, both as regards technical assistance and facilities for producing pieces" (in Lloyd, 1978, p. 130).

and was made chief designer; John Herriott, a manager with extensive experience in the development of (piston) engines and had been reallocated to Rover by the Aeronautical Inspection Directorate; and Denis Drew, who was put in charge of the test bed equipment department (testing equipment is often the weak link in the development process). Most of the factory workforce was local and remained under the new ownership; the majority of the other members came from Derby, including Christopher Ainsworth Davis, who was made assistant chief designer and brought with him "the basic Rolls-Royce design standards and expertise" (Hooker, 1984, p. 80); Ron Kibby, who was put in charge of detail design and was "the essential link between the creators of the engine and the men who have to make it" (Hooker, 1984, p. 80); Robert Plumb, who was an expert on lubrification (one of the problems of the Whittle engine) and had considerable experience with the mechanical engineering of the Merlin; Harry E. Gresham, the chief metallurgist at Derby, who made frequent visits to Barnoldswick, where he established a metallurgical laboratory under the control of his assistant Douglas Hall; Freddie Morley, who came from the Advanced Project Design at Derby and later became chief designer at Derby; and Harry Pearson, who had worked in developing the ejector exhaust system on the Merlin. Rolls-Royce's management also brought with them their quality standards, expertise, and practices, which helped accelerate the pace of the W.2B development. For a summary of the key events, organizational units, people, and resources involved in developing each aeroengine, see Table A1. For further technical details on aeroengines and illustrations of a typical Rolls-Royce design office, see Figures A1 and A2 (in the Online Supplement), respectively.

As it became more familiar with the centrifugal turbojet aeroengine, Rolls-Royce decided to reduce its reliance on Power Jets. In February 1943, after the first WR.I had passed its acceptance test, Rolls-Royce told the MAP that future WR.I-related contracts should be placed directly with Rolls-Royce. In July 1943, Hives transferred the WR.I project from Derby to Barnoldswick and requested that the MAP cancel the original contract for WR.I engines that had been placed with Power Jets. Power Jets was very disappointed when Rolls-Royce reneged on their November 1942 agreement to produce the W.2/500 and decided in April 1943 to embark on a new turbojet development, the B/37, which it designed using some of Power Jets's drawings but without much consultation with Power Jets.[18] The first B/37, later renamed the *Derwent*, ran in July 1943, and its first flight trials were made in an F.9/40 in April 1944.

5.3 | The turboprop

The introduction of the *turboprop* aeroengine in the postwar period ushered in the jet age of civil aviation. The new performance requirements for an aeroengine used in civil aviation included: high reliability, low maintenance costs, and excellent safety records that exceeded those of military aviation, where speed and power were the defining performance requirements. Understanding and managing these different performance requirements proved extremely challenging for several successful incumbents (e.g., Curtiss-Wright and General Electric). Anticipating this challenge, on December 23, 1942, the British government formed a committee under MAP Lord Brabazon of Tara with the explicit task of planning for the postwar needs of British

[18]"Eclectic like the WR.1," the engine combined Power Jets's W.2/500's compressor and turbine with the "straight-through" combustion layout and superior mechanical design of Rover's B/26 (a production-friendly version of the W.2B), and "Rolls-Royce's production and supercharger expertise" (Giffard, 2016, p. 89).

civil aviation (Pugh, 2001). The country had focused primarily on combat aircraft during the war; postwar, the nation's production priorities had to be reconsidered.

Indeed, the whole British aviation industry entered postwar civil aviation at a huge competitive disadvantage *vis-à-vis* its counterpart in the United States, which was heavily funded by the government and had emerged almost unscathed—even reinforced—after the war efforts. While Great Britain had concentrated its efforts on combat aircraft during the war, the United States never stopped developing civil aircraft. In fact, at the end of the war, the United States had an impressive collection of excellent short-, medium-, and long-range transport aircraft manufactured by Douglas and Boeing and powered with aeroengines by Pratt & Whitney, Curtiss Wright, and other major US-based manufacturers (Pugh, 2001). The only advantage the British aeroengine (and aircraft) manufacturers had was their experience with turbojets, starting with the centrifugal pure turbojets designed by Whittle and prototyped by Power Jets.

The world first scheduled *turboprop* airline service was launched by British European Airways (BEA) on April 18, 1953. This was a pivotal moment both for Britain's aviation industry and civil aviation as a whole. On this date, the Vickers Viscount, powered by Rolls-Royce's *Dart*—panels (e) and (h) in Figure A1—entered service. The Viscount appealed to passengers because of its low noise and vibration levels compared to the existing piston aeroengine and gave BEA a competitive advantage on routes where their competitors long had claimed most of the traffic (Saravanamuttoo, 1987).

The turboprop was a resounding success from the very beginning: "The evidence of the past three years' successful and profitable operation of the Viscount with its *Dart* engines leaves no room for doubt that, even at this stage of its development, this type of engine is a better prime mover, both mechanically and operationally, than the piston engine, for medium-range transport aircraft. It offers simplified maintenance and improved passenger comfort" (Corson, 1956, p. 604). The introduction of the *Dart* marked the final demise of the piston aeroengine in civil aviation. The *Dart* was the first profitable aeroengine and remained in production for more than 40 years, making it the longest-running design in aeroengine history. It also was adopted for important military applications—for example, in the P-3 Orion Anti-Submarine Warfare aircraft and the ubiquitous Hercules military transport (Saravanamuttoo, 1987), both of which are in service today. To explain the *Dart*'s success, it is important to examine how Rolls-Royce reallocated its resources in the face of the new performance requirements and redirected its efforts to meet the needs of civil aviation. These decisions eventually led Rolls-Royce to become one of the dominant players in the turboprop aeroengine market.

5.4 | Rolls-Royce: Resource reallocation in the turboprop phase

On September 30, 1943, former Minister of War Production Lord Beaverbrook wrote to Hives:

> "Questions arise in my office concerning civil aviation now and after the war. It has been said in the House of Commons that engines now turned out by Rolls-Royce and other engineering firms will not be suitable for civil aircraft when the war is over" (reported in Pugh, 2001, p. 257).

Echoing the concerns raised by the Brabazon Committee, this letter foreshadowed some of the challenges Rolls-Royce had to overcome in the postwar era. Although it had emerged as the leading aeroengine firm, Hives warned the board of directors in June 1945 that intense competition could be expected from other aeroengine firms, many of which had produced aeroengines by the end of the war. In particular, he stated:

> "The very fact that we have been able to design an entirely new jet engine, put it on the test bed for the first time and complete a 100 hours test without looking inside it indicates that as regards jet engines they are relatively simple to design and produce, and as soon as things become simple then one must expect keen competition. Generally we rely on making difficult products where it does not pay people to compete. Fortunately, the tendency on jet engines will be for them to become more complicated and therefore more difficult, which is more in our line of business" (reported in Lloyd, 1978, p. 138).

In 1944, Lionel Haworth began work on the RB39 (the *Clyde*) at Derby. It was the firm's first purpose-built turboprop and "exploited continuities with both piston engine practice and the firm's growing turbojet expertise" (Giffard, 2016, p. 91). Although the first turboprop—the RB50 or *Trent*—had been made in 1944 at Barnoldswick, Rolls-Royce's interest in making a turboprop aeroengine dated back to July 25, 1941, when it requested two contracts for work on new turbojet aeroengines from the MAP. One of these contracts contemplated a turbojet/turboprop aeroengine, which "was advertised as a promising postwar engine that would offer a much higher power to weight ratio than the contemporary Bristol Hercules XI piston engine (Bristol was Rolls-Royce's chief competitor in making piston aeroengines)" (Giffard, 2016, p. 78). Although only five *Trent* were ever built, Rolls-Royce took away valuable lessons that proved useful for subsequent turboprop aeroengines like the RB39 *Clyde* (e.g., using helical rather than toothed reduction gears).

The *Clyde* was the first turboprop aeroengine to pass military and civil tests. Following Hooker's suggestion, the *Clyde* employed a two-shaft design with an axial compressor that built on the Metropolitan-Vickers's axial F2 (Metrovick F.2) for the low-pressure section, and a single-sided centrifugal compressor scaled up from the Merlin 46 supercharger (McKenzie, 2001). The *Clyde* was a long aeroengine with an axial LP (low pressure) compressor in front of what was, in effect, a scaled-down *Derwent* aeroengine. The *Clyde* resulted from the close collaboration between two teams: one at Derby under Lionel Haworth—who had joined Rolls-Royce (in Derby) in 1936, began working to adapt the Merlin engine to naval powerboats in the summer of 1938, and then took charge of the project from 1939 onward—and the other at Barnoldswick under Stanley Hooker and Adrian Lombard (see Table A1). As with the *Trent*, the reallocation of human and organizational resources was fundamental for developing the turboprop. Haworth's team at Derby designed the aeroengine's compressors following Hooker's suggestion, while Lombard's Barnoldswick team devised the aeroengine's combustion system and turbine. The design of the *Clyde* began in March 1944, and the aeroengine was built at Barnoldswick, where John P. Herriot—a manager reallocated from Derby—led the aeroengine development "almost alone" (Giffard, 2016, p. 92). Testing began on August 5, 1945.

The *Clyde* program was terminated in 1949 because Hives felt that pure-jets (e.g., the *Avon*) were the future. Although the *Clyde* did not bring home profits, the engine still benefited the company because the firm's designers learned from the experience and put their new knowledge to good use when Rolls-Royce developed the RB53 *Dart*. First run in 1946, the *Dart* powered the Vickers Viscount on its maiden flight in 1948. The flight between Northolt and Paris–Le Bourget of a *Dart*-powered Viscount on July 29 of the same year was the first flight by a turbine-powered aircraft to be regularly scheduled by an airline. The Viscount also was the first turboprop-powered aircraft to enter service with BEA in 1953. Forty years later, in 1987, the *Dart* was still in production when the last Fokker F27 Friendship and Hawker Siddeley HS 748 were produced (Turner, 1968).

At the end of the war, the AJ65 (axial turbojet), later renamed the *Avon*, became the focus of postwar turbojet efforts at Derby, where Hives concentrated work on the turbojet in 1946. This decision meant that the axial engine that Arnold Alan Griffith had continued to work on throughout the war—despite requirements that priority be given to the centrifugal turbojet—became the main focus at Derby. Alfred Cyril Lovesey, a key figure in the development of the Rolls-Royce Merlin aeroengine during the war, was put in charge of Derby's *Avon* development team. Rolls-Royce thus began its transformation into a maker of gas turbine aeroengines, and the *Avon* was the first in a long line of successful axial turbojets. In the postwar period, they proved ideal for both civil and military aircrafts.

5.5 | The turbofan

Most modern airliners use turbofan aeroengines due to their fuel efficiency and high thrust at take-off. In contrast, early turbojet engines were not very fuel-efficient since the materials and technology available at the time severely limited their overall pressure ratio and turbine inlet temperature. Thanks to the turbofan's improved propulsive efficiency and significant decrease in noise (Saravanamuttoo, 1987), it gradually became dominant after 1960.

5.5.1 | Rolls-Royce: Resource reallocation in the turbofan phase

In Great Britain, Griffith had been proposing "bypass" or turbofan engine designs since the early 1930s. However, during World War II, the UK prioritized simpler turbojet designs for their use in military applications. In 1946, Rolls-Royce realized that given the advances made with existing aeroengines such as the *Avon*, it was important to begin work on more advanced concepts like the bypass. Griffith, who by this time was Rolls-Royce's chief engineer, suggested building a purely experimental bypass design with parts coming from the *Avon* and another experimental jet engine, the AJ.25 (also known as the *Tweed*).

In terms of resource reallocation, the development of the turbofan started at Derby in the late 1940s under the supervision of Geoffrey Wilde, who had joined Rolls-Royce in 1938. Previously, starting in 1943, Wilde had been the head of the compressor and supercharger department at Derby, doing much of the design work for the compressors and contributing to the improvement of the Merlin supercharger. Starting in 1947, following Stanley Hooker's departure to Bristol Engines, Wilde began leading the design and development of the AJ65 *Avon* axial-flow jet engine. At this time, Alfred Cyril Lovesey, who had joined Rolls-Royce in 1932 and worked on the Merlin's development program, took charge of the *Avon* development team at Derby, while Wilde headed the development of the compressor for the *Conway* (code RB80).

The design process began in October 1947 and the first engine ran in August 1952. Development continued until the first flight in August 1955. This was the world's first turbofan engine to enter service and was built specifically for large, long-range subsonic transport aircraft. Although the *Conway* was originally designed for a bomber—a project that was later canceled—Rolls-Royce managed to get it onto "the Boeing 707 and the Douglas DC-8," and some other airliners (Pugh, 2001, p. 57; see also Stroud, 2018). The *Conway* was used only briefly during the late 1950s and early 1960s before being replaced by other turbofan designs. These new civilian turbofan engines of the 1960s—such as Rolls-Royce's *Spey* and Pratt & Whitney's JT8D—had bypass ratios closer to 1 and were actually more similar to their military equivalents.

6 | FINDINGS

In 1951, a one-stop flight operating with a Douglas DC-6 powered by four piston engines could travel between New York City and Los Angeles in 10 h and 20 min. In 1961, the same route was covered by a Boeing 707 with a non-stop flight lasting 5 h and 15 min—approximately the same flight time as today (Pauly & Stipanicic, 2022).[19] While the Boeing 707 reestablished American hegemony in civil aviation in the postwar years, one of its successful versions was powered by a British aeroengine: the Rolls-Royce *Conway* (Pugh, 2001), which was the culmination of a series of key events and reallocation decisions that resulted in the turbojet, turboprop, and turbofan jet engines. This evolutionary process began in 1939, when Hives recruited Griffith to work on gas turbine aeroengines, and continued with Rolls-Royce's decision in January 1942 to collaborate with Power Jets as a subcontractor on the design of a new centrifugal turbojet aeroengine. Interestingly, the aeroengine market leaders today are three companies that have been designing and producing jet engines from their first introduction into civil aviation: General Electric, Pratt & Whitney, and Rolls-Royce. However, Rolls-Royce alone was the main driving force of the jet revolution in civil aviation.

Despite its recognized excellence in the old piston and new gas turbine technologies, in hindsight Rolls-Royce's success in postwar civil aviation is not as obvious as it might seem. After the war, Rolls-Royce lacked the expertise in civil aviation of other competitors (both British and American),[20] yet it not only survived the aeroengine revolution but thrived, becoming a dominant player in the postwar aeroengine market. While different lenses could be adopted to examine this (complex) revolution, we posit that the resource reallocation processes that took place at Rolls-Royce starting in 1941—a decade before the first deployment of aeroengines in civil aviation—illuminate how and why this was possible. To better understand the processes involved in resource reallocation and derive some general principles from our data, we drew on Carignani et al.'s (2019) technological evolution model.

By highlighting the role of the horizontal transfer of functional modules, especially during the early stages of a new systemic innovation, the model helps uncover the key *processes* underlying resource reallocation and elucidate how their relative importance in shaping systemic innovation varies across different phases in an industry's evolution. An in-depth discussion of evolutionary models in technology goes beyond the scope of this article (for a more detailed discussion, see Cattani & Malerba, 2021; Cattani & Mastrogiorgio, 2021); yet, focusing on the evolutionary phases (described in Table A2 in the Online Supplement) is important to understand *how* and *why* the horizontal transfer of functional modules enabled Rolls-Royce to play a key role in each systemic innovation.

[19]Although cutting the flight time by half in just a few years was an astonishing improvement in air travel, the important benefits (for both passengers and the airlines) were the smoother functioning of the aircraft—which made the flight much more comfortable—and the aeroengine's reliability, safety record, and low maintenance costs.
[20]For instance, Bristol in the United Kingdom and Curtiss-Wright in the United States.

6.1 | Resource reallocation over time

The first jet engines capable of functioning on their own power were not created by dominant incumbents, but by two "inventive institutions" (Giffard, 2016): Power Jets in the United Kingdom and Heinkel in Germany. These institutions demonstrated the feasibility of the turbojet for the first time. In the United Kingdom, Power Jets did not start from scratch: instead, the key functional modules needed to make a functioning turbojet came from several industries, including the piston aeroengine industry. In particular, the following functional modules proved critical:

- *Turbine*—A new functional module to the aeroengine industry that was transferred, with important modifications, from the steam turbine industry. Its design, prototyping, and manufacturing posed critical challenges related to structural design and temperature-resistant alloys. British Thomson-Houston, a manufacturer of steam turbines, was a key collaborator.
- *Combustion chamber*—A functional module whose technology was already known in the combustion equipment industry but had to be redesigned to meet the critical performance level of a jet engine in terms of burning intensity. Laidlaw, Drew & Company, a Scottish firm specializing in burners and combustion equipment for other purposes, was a key collaborator.
- *Compressor* (supercharger)—Designed and produced by aeroengine manufacturers like Rolls-Royce and their first-tier suppliers (e.g., General Electric).

Figure 2 traces the evolution of these functional modules and their industry origins.

Power Jets's ability to combine these functional modules into a new aeroengine largely can be explained by the fact that these modules were sufficiently "preadapted" (Carignani et al., 2019; Cattani, 2006). This made possible—albeit at a considerable effort—their integration into a new complex artifact (i.e., an aeroengine that could run under its own power).

Following the initial phase in which horizontally transferred functional modules from several industries are acquired (*acquisition* phase, see Table A2), the emergence of a functioning prototype that can be replicated successfully marks the beginning of the *retention* phase. This turning point was reached in 1937, when the first run of a pure turbojet under its own power took place almost contemporaneously in Germany and the United Kingdom. In the United Kingdom, this event occurred on April 12, 1937, when Power Jets successfully tested Whittle's WU engine. During the retention phase, the value of a new technological artifact is recognized because its performance can be measured and assessed and, therefore, replicating the functioning artifact is possible. This critical moment occurred when Rolls-Royce—at the time the leading manufacturer of piston aeroengines in the United Kingdom—became interested in Whittle's pure turbojet. Following his first visit to Power Jets in January 1940, Stanley Hooker convinced Ernst Hives to visit Power Jets in August of the same year. Despite his initial skepticism about Whittle's aeroengine performance, Hives eventually decided to involve Rolls-Royce in the development of the centrifugal pure turbojet and, in January 1942, Rolls-Royce agreed to work with Power Jets as a subcontractor. In addition to reallocating the necessary internal resources, Rolls-Royce also transferred and integrated other resources from outside. For example, to manage the large-scale production of the turbojet, it took over two jet engine factories, Barnoldswick and Clitheroe, which the government had assigned to Rover in 1940.

Figure 3 provides a detailed illustration of the reallocation of resources during this specific phase and the crucial role of Rolls-Royce's expertise in both piston engines (at the compressor/supercharger level) and general purpose aeroengine technology—depicted in blue and red, respectively.[21] By zooming in on the section of the graph in Figure 2 that corresponds to the *Welland*, Figure 3 graphically traces the key reallocation events spearheaded by Ernest Hives that resulted in development of this turbojet aeroengine. This analytical figure also builds on the evidence discussed in the "resource reallocation in the turbojet phase" section. As shown in the figure, *different* types of resources were reallocated, including organizational and human resources (in the middle of the figure), knowledge of key aeroengine components (primarily associated with piston engines and general-purpose aeroengine technology, on the left), and physical plants and other types of resources (on the right). Figure 3 further illustrates that the horizontal transfer of functional modules is critical for understanding the early-stage development of a complex artifact (here a new aeroengine). This development typically implies the reallocation of organizational, human, and technical resources from different areas of expertise that must then be properly integrated. However, as we discuss in the next section, not all firms possess the capability to reallocate and integrate resources, even when those resources are available in-house.

As mentioned earlier, the high-altitude fighter-interceptor was the first military niche in which the new aeroengine demonstrated better performance (in terms of speed) than the piston engines that powered state-of-the-art fighters. After the Battle of Britain in 1940, the new aeroengine was selected for this niche when, in July 1941, British Prime Minister Winston Churchill decided "to push its production as a defense against high-altitude German bombers" (Carignani et al., 2019, p. 521). This event marked the beginning of a *selection* phase, and thus the transition from experimental aeroengines to production aeroengines. Accordingly, Rolls-Royce focused most of its resource reallocation efforts on the development of the *Welland*, Britain's first operational turbojet, and then on the *Derwent*. Rolls-Royce relied on existing organizational and human resources, as well as on its experience in piston engines.

In 1942 and again in 1943, Rolls-Royce reallocated large amounts of its internal resources (see Table A1). Interestingly, while compressors (superchargers) were a peripheral (yet important) module of piston engines, they became a core functional module in the centrifugal turbojet architecture. This explains several of the key resource reallocation decisions made around this time, such as when Hives decided to transfer all experimental work on jet engines to Barnoldswick, and Stanley Hooker (from the Derby unit) was given "more or less *carte blanche*" to choose his team members. Moreover, thanks to its collaboration with Power Jets, Rolls-Royce had the opportunity to access functional modules that were horizontally transferred from other industries, and the ability to both integrate these modules into a functioning artifact (the experimental aeroengine) and replicate them.

In the postwar years, the turbojet aeroengine was used in several niches in military aviation—from bombing to transportation—before expanding into civil aviation. This expansion into other niches marked the *fixation* phase. While civil aviation posed several challenges to Rolls-Royce, key to explaining its success was the decision to embrace the inferior—but simpler—two-stage centrifugal compressor architecture rather than the more advanced (and widely recognized as superior) axial design proposed by some competitors. By the time Rolls-Royce made that decision, it already had gained experience in turboprop technology, as it had

[21]Other types of expertise, including those related to combustion systems (transferred from *other* industries, as seen in Figure 2, but potentially *internal* to Rolls-Royce), are depicted in black.

designed, prototyped, and tested in flight two different turboprop engines: the *Trent* and the *Clyde*. Despite the challenge of entering a market niche in which its competitors were more competent, Rolls-Royce nevertheless was able to define the required performance for civil aviation due to the superiority of its *Dart* turboprop engine. It surpassed any piston engine in terms of speed and passenger comfort and bested its competitors' turboprop engines in terms of reliability and safety.[22] This ultimately led aircraft manufacturers and airlines to select the *Dart*.

The origins of the first turboprop reveal that the *horizontal transfer* of existing functional modules remains relevant even after the emergence of a new technological trajectory (the turbojet). Rolls-Royce built its first turboprop, the *Trent*, by recombining an adapted *Welland* aeroengine with a gearbox and a propeller (see Figure 2). This is another paradigmatic case of horizontal transfer, as both functional modules were transferred from the aeroengine industry—a transfer facilitated by Rolls-Royce's capacity to replicate (with modifications and improvements) modules from aeroengine technology. For example, it had designed "the gearbox—a functional module which connects the turbine to the propeller in the *Trent* turboprop—at its Derby plant" (Carignani et al., 2019, p. 522). The *Trent* was the product of collaboration between the Derby and Barnoldswick teams that "exploited continuities with both piston engine practice and the firm's growing turbojet expertise" (Giffard, 2016, p. 91). While the Derby team designed the gearbox connecting the propeller to the turbine by relying on Rolls-Royce's expertise in piston engine design and production, the Barnoldswick team contributed new expertise to the turbojet thanks to its collaboration with Power Jets.

After the *Trent*, Rolls-Royce developed its first purpose-built turboprop, the *Clyde*, an ambitious aeroengine project that adopted a hybrid compressor by integrating an axial low-pressure stage and a centrifugal high-pressure stage (see glossary under Figure 1). This advanced aeroengine was followed by the much simpler *Dart*. Improvements in the turboprop assembly (e.g., the redesign of the gearbox and other critical functional modules) was central to the success of the *Dart* and represented the *amelioration* phase. The *Dart* marked a notable change in the history of aeroengines: it was the last engine in which the horizontal transfer of key functional modules (the gearbox and the propeller) played a crucial role. Subsequent innovations, including the introduction of the turbofan—for example, the *Conway*—resulted from a typical process of vertical descent (Carignani et al., 2019).[23] Thus, the *Dart* divides the graph in Figure 2 into two separate areas, with innovation regimes—and associated resource reallocation processes—following different rules.

6.2 | Resource reallocation as a dynamic integrative capability: Evidence from the case

The case analysis reveals that Power Jets's early success was short-lived even though it pioneered the first centrifugal turbojet by combining three existing functional modules (compressor, combustion chamber, and turbine). The main reason Power Jets ultimately failed to

[22]George Edwards at Vickers Aviation wanted the *Dart* as opposed to an engine based on Griffith's axial compressor—which Rolls-Royce's competitors also were using—because the axial compressor was still unproven. In 1948, he told the Royal Aeronautical Society: "Centrifugal compressors [as superchargers] have been running in piston engines for many years and their rugged construction and freedom from icing will not be present in an axial compressor" (reported in Pugh, 2001, p. 38).

[23]Even if the horizontal transfer of functional modules was less relevant, the turbofan entailed a reconfiguration of key functional modules (Brusoni & Prencipe, 2009), like in the case of the other two systemic innovations.

become a dominant player during the large-scale production of jet engines is that it "persistently characterized production as a derivative exercise rather than a creative one" (Giffard, 2016, p. 88)—thus framing the making of new aeroengines in terms of the theoretical separation between research and development. This separation was not an issue during the prototyping phase, when the goal was to demonstrate that a functioning jet engine in principle could be produced, but it became problematic during the production phase as Power Jets lacked the large-scale testing, development, and production capabilities of some large incumbents, like Rolls-Royce.

Even a large player like Rover—a car manufacturer that was experienced in the production of (piston) car engines but not in aeroengines and had collaborated with Power Jets prior to the entry of Rolls-Royce—soon discovered that testing, development, and production challenges were significant. Unlike Rolls-Royce, Rover had no experience using special materials resistant to high temperatures or the tools to handle them, nor did it have other production routines typical of the aeroengine industry (Lloyd, 1978). It therefore could not take advantage of the "continuities" between piston and jet engines (Giffard, 2016). So, why did large incumbents like Rolls-Royce dominate the production phase rather than inventive institutions like Power Jets—which were instrumental during the prototyping phase—or large players like Rover? Additionally, what are the organizational implications for resource reallocation?

Based on available historical records, a plausible explanation for the success of large incumbents is the role of *integrative capabilities* (Helfat & Campo-Rembado, 2016)—which refer to a firm's ability to coordinate different stages in innovation processes or, in organizational terms, different functional activities typically involved in the development of new technologies and products (see also Helfat & Raubitschek, 2000, 2018; Henderson, 1994; Iansiti & Clark, 1994).[24] Integrative capabilities allow vertically integrated firms to both adapt better and generate a continuous flow of innovations, some of which develop over time in distinct (yet related) businesses. Looking at the trajectory that led to the turboprop (the *Trent*, the *Clyde*, and then the *Dart*: see Figure 2), it is evident how some key existing functional modules of the turboprop—in particular, the propeller and the gearbox—retained their value and so could be reallocated to make the new jet engines. Under these circumstances, "even though integrated firms may lose money if specialized firms enter the market as the industry evolves, integrated firms may choose to bear these losses if the firms can obtain a countervailing benefit from having retained their integrative capabilities when subsequent systemic innovations occur" (Helfat & Campo-Rembado, 2016, p. 249). But why then did Power Jets, with its capability to prototype the first centrifugal turbojet, eventually fail to benefit from its early efforts, as did a large player like Rover?

To answer this question, it is important to consider the modular structure of a complex technological artifact like an aeroengine (Brusoni & Prencipe, 2001) and the extent to which a firm has expertise and/or familiarity with one, a few, or all the functional modules of a complex technological artifact. As a coordination mechanism, modularity involves the partitioning of activities into those that can be carried out independently of each other (Simon, 1962). However, in the early years of a systemic innovation, when the interfaces between modules are still undefined, modules cannot be adequately partitioned. Hence, when faced with systemic innovations, firms are better off remaining integrated and keeping communication, coordination, and accompanying support systems in-house (Helfat & Campo-Rembado, 2016).

[24]In a private conversation with the authors, Constance Helfat pointed out how integrative capabilities subsume reallocation capabilities, with the latter being a subset of the former.

The trajectory leading to the turboprop is instructive in this respect. It was marked by the horizontal transfer of existing functional modules, in particular the propeller and gearbox (see Figure 2). The only integrated firms that eventually succeeded were those that had expertise and/or familiarity with functional modules at multiple modular levels and, therefore, the capacity to integrate them into a new aeroengine type that met performance requirements of downstream users (e.g., aircraft manufacturers, airlines, etc.). As the case analysis has shown, Rolls-Royce had the capacity to design and produce several functional modules—like the propeller and gearbox in the case of the turboprop, and the compressor in the case of the turbojet. Crucially, it also had the capacity to integrate them, which it developed as a result of its prior experience making traditional piston aeroengines. This experience and know-how, which "touched on aspects of gas turbine design, whether compressors, turbines, or exhaust nozzles [...] brought significant advantages because of the intricacy of aero-engines and the accuracy of their manufacture" (Giffard, 2016, p. 146). In addition, Rolls-Royce had a deep understanding of user needs and performance requirements at the higher modular levels. Thanks to its collaboration with different players, it could incorporate into its aeroengine designs the needs and requirements of aircraft manufacturers (e.g., the Vickers with the turboprop); airlines (e.g., the *Dart*-powered Vickers Viscount that entered into service with BEA in 1953); military air forces like the Royal Air Force; and institutional players like the Brabazon Committee (Pugh, 2001).[25]

Small inventive institutions like Power Jets and large players like Rover were less favorably positioned. Power Jets was able to integrate existing functional modules—compressor, combustion chamber, and turbine—into the first experimental centrifugal turbojet aeroengine, but it had neither the capability to produce any of them nor Rolls-Royce's level of expertise and familiarity with higher modular levels. Lacking the ability to integrate across production stages, Power Jets failed to become a dominant player during the phase of large-scale jet engine production. Thus, an important insight of our case study is that a perspective based on modularity—and its different levels—is key to understanding when a firm's integrative capabilities are likely to be effective in the face of a systemic innovation: integrative capabilities are *most* effective when firms have developed expertise and familiarity with many (or most) of the functional modules at different modular levels of a complex technological artifact.

6.3 | Generalizing from Rolls-Royce

Why do *some* firms reallocate their resources "more effectively than other firms"? (Helfat & Maritan, 2024, p. 1). Our case demonstrates that a firm's "reallocation capability" resides in a set of specific organizational arrangements and routines shared by Rolls-Royce and a few other firms. In line with its strong R&D and engineering-based culture, Rolls-Royce usually develops new technologies and businesses by leveraging its knowledge base. The belief that innovation is important always has been an integral dimension of its corporate culture, contributing to creating an environment where new ideas and initiatives are generated continuously, and errors or mistakes are seen as valuable learning opportunities. This is consistent with evidence regarding other companies like Corning and 3M, which have remained consistently innovative over time by following a very similar approach (Cattani, 2006; Gundling, 2000).

[25]During the early years of a new technology—when the interfaces between modules are still undefined, modules are not yet mirrored in the organizational structure, and "system integration" (Hobday et al., 2005; Prencipe, 2000; Prencipe et al., 2003) is difficult—such high-level interactions are particularly important.

In Rolls-Royce—unlike in inventive institutions (e.g., Power Jets)—a close interaction between internal design, prototyping, testing, and development always has been at the heart of its ability to pioneer groundbreaking technologies over time. The success of this approach is not unique to Rolls-Royce: the invention and development of the first low-loss optical glass fiber for long-distance communications in the mid-1960s likewise is instructive. In 1966, Charles Kao and George Hockham—both engineers and researchers at the Standard Telecommunications Laboratories of the International Telephone and Telegraph's (ITT) subsidiary in England—published a paper in the Proceedings of the Institution of Electrical Engineering in which they "demonstrated for the first time the theoretical feasibility of optical communications" (Cattani, 2006, p. 298) and speculated that an extremely pure type of glass such as fused silica could be used to make glass fibers with the required characteristics for optical communications. However, they offered no practical solution to several fundamental questions, in particular the very high melting temperature of fused silica. Although its engineers had done most of the theoretical groundwork for fiber optics, ITT—which, at the time, was one of the largest US-based conglomerates where resource reallocation followed a strict financial logic (quick return on investments)—concentrated not on fibers, whose production was outsourced, but on cabling. Unlike other firms (including ITT), Corning was the only firm in the early 1960s with a furnace that could melt fused silica and draw it into fibers; in other words, Corning was the only firm with design, prototyping, testing, and development capabilities that could be used to resolve some of the challenges involved in making fiber optics technically and commercially feasible (for more details, see Cattani, 2006). The fact that these capabilities were unavailable to their competitors positioned Corning to become the leading innovator in fiber optic technology.

As previously mentioned, Rolls-Royce had the capability to effectively coordinate the different functional activities involved in creating new technologies. Integral to this capability was a deep understanding of user needs and performance requirements at higher modular levels. Rolls-Royce's emphasis on the primacy of science and engineering did not prevent the company from being sensitive to the changing needs and performance requirements of airline companies. This contrasts with technology-driven firms that, surprisingly, downplay the importance of paying attention to user needs. For instance, Edwin Land, the founder of Polaroid, saw science as a tool to develop products that satisfy deep needs that could not be understood through market research. Despite its huge success in instant photography, Polaroid viewed digital imaging primarily as a technological shift rather than a shift in user needs. As a result, most investments were directed at developing new technical capabilities, neglecting user needs. As one digital imaging manager put it: "Polaroid didn't have a sense of the distinction between research and product development. It was all mixed up. Many people were totally oblivious to what it means to get a product really developed and make it ready for the market place" (in Tripsas & Gavetti, 2000, p. 1153).

The formation of dedicated *cross-functional teams* (Helfat & Maritan, 2024) is key to explaining Rolls-Royce's ability to effectively reallocate internal resources, often from other related businesses (e.g., the automobile industry). Similarly, Corning's pioneering work in fiber optics in the mid-1960s was the result of the efforts of a cross-functional team that consisted of Donald Keck and Peter Schultz under the guidance of Robert Maurer (an industrial physicist). Before joining the team, Peter Schultz was doing research on fused silica in the glass chemistry department. Robert Maurer had worked with fused silica since 1956 and had researched light scattering, a major cause of fiber attenuation. He also was one of the Corning scientists who had been investigating glass-based lasers since the late 1950s. Donald Keck had studied molecular spectroscopy before joining Corning in 1968. Corning's creation of a team consisting of individuals with different areas of expertise facilitated the reallocation of critical resources, most of which were available in-house.

Other organizational practices and routines were also critical. Retaining long-tenured employees helped preserve the integrity of the firm's knowledge base, allowing for new syntheses as novel opportunities came along. For instance, before becoming involved in the development of fiber optics, Robert Maurer gained valuable experience with light scattering and quantum optics. Low turnover among managers, senior researchers, and engineers ensured continuity between past and current R&D. Although previous research has argued that *organizational memory* does not necessarily coincide with individual memory (e.g., Nelson & Winter, 1982; Walsh & Ungson, 1991); yet, individuals often are "the sole storage point of knowledge that is both idiosyncratic and of great importance to the organization" (Nelson & Winter, 1982, p. 115). Organizational memory—that is, the preservation of relevant skills and knowledge across different generations of scientists—helps explain why the innovation approach of companies like Rolls-Royce reflects a deep-seated belief that while problems tend to change continuously, certain skills and knowledge remain valuable. The value of these skills and knowledge is in fact reaffirmed whenever similarities "between old solutions and new problems" (Hargadon & Sutton, 1997, p. 732) are recognized, including reallocating existing resources to new uses. To preserve this memory, firms such as Rolls-Royce, Corning, and 3M, among others, have asked old-timers—that is, long-tenure scientists and engineers—to remain as consultants even after retirement and serve as mentors and guides to younger scientists and engineers, thus ensuring the continuous transfer of relevant skills and knowledge between generations of employees.

Furthermore, top managers are usually scientists or engineers who have spent their entire careers with the same company and, therefore, can both understand the technological, market, and competitive challenges that innovation entails and work closely with division managers to provide them with the support and resources they need (Helfat & Maritan, 2024)—critical conditions for developing the next breakthrough. Indeed, as the case analysis reveals, Ernst Hives was integral to the development of each of the three innovations (turbojet, turboprop, and turbofan): not only did he act as a champion with Rolls-Royce's top management, but he also worked closely with mid-level managers (e.g., Stanley Hooker and Adrian Lombard), providing them with the resources they needed. Because he had spent most of his working life at Rolls-Royce in various roles and become socialized into its basic values and norms, Hives had a deep organizational memory and a transactive memory—in other words, he knew who knew what (Ren et al., 2006). This helped him recognize others' knowledge and expertise and reallocate the right people to the right teams tasked with developing each new aeroengine type. Moreover, he understood the importance of "patient capital," especially when developing breakthrough technologies.[26] This is consistent with similar roles played by R&D managers in other companies. For instance, William Armistead, Corning's director of research from 1954 until 1971, is credited with increasing Corning's focus on exploratory research, expanding the technical staff to include experts from many disciplines and reallocating resources to sustain innovation until it generated financial returns (Cattani, 2006; Lazonick & Prencipe, 2005). This eventually led to the introduction of many breakthrough technologies at Corning, including fiber optics.

[26]James R. Houghton, former CEO and chairman of Corning, referred to "patient money" to emphasize the idea that any investment in science and engineering only "pays off in time" (Houghton, 1983, p. 13).

7 | CONCLUSIONS

Over the past few years, resource reallocation has received renewed attention among strategy scholars. However, the specific processes through which resources are reallocated over time have remained remarkably understudied. To shed light on these processes, we conducted an in-depth historical case study to examine the role of Rolls-Royce—and the resource reallocation processes involved—in three successive systemic innovations that marked the advent of the modern aeroengine industry: the turbojet, the turboprop, and the turbofan. In particular, we focused on the horizontal transfer of functional modules at Rolls-Royce. We also explored the role of specific organizational arrangements, with an emphasis on the (dynamic) capabilities of Rolls-Royce to integrate successfully at different modular levels.

Our study has several implications for the recent debate on resource reallocation. Two pillars of research on resource reallocation are the works of Penrose (1959) and Chandler (1962). Both explore the role of resource accumulation on the scope of a firm and its relationship to the firm's organizational arrangements. In particular, the Penrosian concept of resource—the fact that a resource has a variety of possible *uses*, often unforeseen and emerging over time—is important (Andriani & Cattani, 2016; Cattani, 2006; Cattani & Mastrogiorgio, 2021; Felin et al., 2016) as it challenges the idea that resource uses are given *ex ante*, immediately instantiated, and out there ready to be grabbed at some point (Folta, 2021). So, where do new resource uses come from? We addressed this question with an in-depth, historical case study of Rolls-Royce and have discovered that while new uses for a firm's resources can have technological origins (Amore & Mastrogiorgio, 2022), the evolution of modular artifacts is driven by processes of horizontal transfer that prompt different waves of systemic innovation.

The previous arguments resonate with an alternative yet neglected lens on resources—and the options embodied in them—based on the concept of "shadow options" (Bowman & Hurry, 1993; Kogut & Kulatilaka, 2001), though the connection between shadow options and the evolution of modular artifacts has not yet been fully explored. At the basis of shadow options lies the view of resources as a bundle of (real) options for future strategic choices. The logic underlying "a shadow option is distinct from the logic of other types of options, whereby an initial upfront investment is deliberately made to achieve a specific end (e.g., an option to grow)" (Andriani & Cattani, 2022, p. 1195). Instead, shadow options are those options that, to be struck, "must first be recognized" (Bowman & Hurry, 1993, p. 763). Support for this concept can be found in a few recent studies that suggest distinguishing between a resource and its possible uses, some of which are in a "latent" state and emerge, over time, in complex and highly contextual ways, often driven by technological developments (Andriani & Cattani, 2016, 2024; Cattani & Malerba, 2021; Cattani & Mastrogiorgio, 2021). This logic has important implications for the way we think about resources in the context of strategy. Given the wide range of possible uses for any given resource, it is particularly challenging for organizational and market actors "to fully account for, exhaust, or price all of these possibilities" (Felin et al., 2021, p. 6). This links back to Penrose's (1959) early insight that resources embody "a range of potential productive services [i.e., uses], *most of which will remain unused*" (p. 534, emphasis added). These uses often emerge from "within the firm" (Levinthal & Wu, 2024) and a resource's "idiosyncratic deployments" (Folta et al., 2016; Kor & Mahoney, 2004). A firm capitalizes on a resource's potential when it deploys the resource for new applications for which it was not originally created or acquired (Cattani, 2006)—a capability that is not equally possessed by all firms.

Finally, our study has implications for other debates on resource reallocation, two of which are worth mentioning. First, we examine a new aspect in the emerging debate on organizational structures and resource reallocation (Levinthal & Wu, 2024) by highlighting the role of integrative capabilities in facilitating the horizontal transfer of functional modules in the early development stage of a systemic innovation. Second, while we do not explicitly adopt a microfoundation lens on capabilities (e.g., Felin et al., 2012; Sirmon, 2021), the paper clarifies how understanding resource reallocation requires examining the complex interaction between individuals, organizational structures, and contextual factors over time. We hope that our findings will stimulate future studies to further explore this relationship.

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DATA AVAILABILITY STATEMENT

This is a historical case study that uses both archival data and published work. Therefore, we do not have a real data set. All the sources from which our historical and technical information was collected are mentioned in the paper.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX

DATA ANALYSIS

As is typical in historically oriented research (e.g., Argyres et al., 2019; Hargadon & Wadhwani, 2023; Kieser, 1994), our analysis proceeded iteratively: we went back and forth with our theoretical ideas and empirical findings to develop a more nuanced understanding of the historical evidence. Specifically, the analysis was carried out through the following three steps:

***Step 1*—Analysis of the context**. We started our analysis by focusing on the historical context in which the three systemic innovations occurred: the revolution in the aeroengine industry that began in the late 1930s, developed during the years of World War II, and continued into the postwar period of civil aviation. Relying on the rich historical evidence collected from various sources, we first compiled a preliminary timeline of the main events and identified the key actors involved in each episode to better understand the contextual conditions in which Rolls-Royce's resource reallocation decisions were made.

***Step 2*—Mapping key resource reallocation decisions**. After developing an understanding of the historical context, defining a preliminary timeline, and identifying the key actors involved, we focused on the specific reallocation decisions that Rolls-Royce made in each episode of systemic innovation: the turbojet, the turboprop, and the turbofan. Whenever possible, we examined these decisions against decisions that other actors made concurrently (either small inventive institutions like Power Jets or other established players like Rover). In particular, we identified the types of resources (technological, organizational, and human) that Rolls-Royce reallocated and determined whether (and where) they were available internally or acquired from outside. Engaging in this microhistorical analysis gave us the unique opportunity to gain deeper insight into the reasons why Rolls-Royce played a key role in each episode of systemic innovation even when—like in the turbojet case—it did not pioneer the new aeroengine type.

***Step 3*—Comparing the three episodes and underlying resource reallocation processes.** Finally, we proceeded to compare the three episodes of systemic innovation. At this point of the analysis, we looked for similarities and differences in the resource reallocation decisions. We unveiled similarities in the processes by which Rolls-Royce reallocated existing resources during the early stages of each systemic innovation. Our comparative analysis and in-depth examination of the three episodes helped us sharpen our theoretical understanding of the role of integrative capabilities in shaping the effectiveness of Rolls-Royce's reallocation decisions and the centrality of the horizontal transfer of functional modules within each episode.

In the following table, we present the rich historical evidence collected from various sources and utilized in the case, categorized based on the type of materials. The triangulation resulting from relying on various data sources and types of historical materials was critical to reduce the risk of retrospective sense-making—that is, imposing meaning on events based on our knowledge of outcomes.

SOURCES OF HISTORICAL EVIDENCE

Type of material	Key sources	Main use in the analysis
Classic and recent works of leading historians of the aeroengine industry (often based on archival sources and interviews with the key actors involved)	Key sources: Boyne and Lopez (1979) Constant (1980) Decher (2020) Giffard (2016) Lloyd (1978) Lloyd and Pugh (2004) Pugh (2001) Schlaifer and Heron (1950) Stroud (2018)	• Gathering historical data on Rolls-Royce. • Understanding Rolls-Royce's history in the broader context of war and postwar aviation, including similar players (like Power Jets and Rover) that were less successful. • Understanding how the history of aeroengines involved various players (including companies, the broader industrial complex, and nations) at different modular levels, ranging from functional modules to aeroengines and airliners at lower and higher levels. • Gathering data on the resource reallocation decisions at Rolls-Royce that influenced the development of each aeroengine type (turbojet, turboprop, turbofan).
Documents from company archives (obtained in book format from the Rolls-Royce Heritage Trust Historical and Technical Series Catalogs)	Key sources: Birch (2016) Griffith (1937) Heathcote (1992) McKenzie (2001)	• Gathering technical details of each aeroengine model that were not available in other sources (e.g., works of leading historians). • Establishing the precise timing of key events that shaped the development of each aeroengine model, including the years of prototyping, development, testing, and launch for each aeroengine model—information of fundamental importance for correctly tracing reallocation decisions. • Gathering details (not available in other sources) on the resource reallocation decisions at Rolls-Royce that influenced the development of each aeroengine type, including information such as the names of engineers involved and the specific departments or projects they were reallocated from and to. • Obtaining illustrations that support the case, such as key models of aeroengines and the structure of a design office at Derby.
Biographies of former engineers working at Rolls-Royce during key events	Key sources: Harker (1976) Hooker (1984)	• Understanding the key events and decisions through the eyes of the people involved. • Better understanding Rolls-Royce's engineering culture, innovation approach, and other vital aspects related to its internal organizational processes and management of its human resources.

Type of material	Key sources	Main use in the analysis
		• Better understanding how resources were reallocated in designing, developing, and manufacturing the various types of aeroengines under consideration. • Obtaining quotes that support the case, akin to historical interviews with the engineers and managers involved, many of whom are now deceased or retired and would otherwise be unavailable.
Informal email exchanges with selected historians and industry experts	Key contacts: H. Giffard (aviation historian) R. Decher (aviation expert) N. Stroud (aviation publisher)	• Assessing the portrayal of the case, including an overall evaluation of its organization, informativeness, and thoroughness. • Checking externally the reported technical details. • Validating our interpretation of main events and the key findings of the case. • Seeking confirmation of the importance of studying Rolls-Royce's organizational processes (resource reallocation decisions).