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RESEARCH

A Mendelian perspective on strategic management: path-dependence and artificial selection in a search for sustainable energy

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Abstract

We present a field-based case study that examines resource allocation as a mechanism with which the Mendelian executive facilitates a robust and ongoing process of search and discovery in extraordinary, complex and changing environments. The field research is conducted in collaboration with a global manufacturer that produces electricity-generating equipment in a search for sustainable energy. The case study illuminates a robust and ongoing process that re-aligns resource allocation iteratively between product development (technology and innovation management) and component procurement (supply chain management) for retaining a firm's stability and functioning. By matching the theory-based predictions with the patterns derived from field-based observations, the case study finds consistency between theory and data. The case study also suggests boundary conditions in space and time, respectively, for extending the two fundamental constructs in the Mendelian Perspective—path-dependence and artificial selection.

Keywords Resource allocation · Experiments · Technology and innovation management · Supply chain management · Sustainable energy

Introduction

A Mendelian Perspective on Strategic Management (Levinthal 2021, 2022) is a giant leap toward a general framework with which scholarly research can situate the challenge of intentionality and adaptation in extraordinary, complex and changing environments. The perspective posits that "The Mendelian executive is a catalyst and cultivator of possibly promising pathways to not fully knowable futures" (Levinthal 2021: 135). With humility, "the Mendelian executive plays a critical role in nurturing the organization to be an effective adaptive entity, but they must do so in the absence of necessarily having a clear or definitive point of view as to what constitutes desired pathways… the task is not breeding a particular variety of roses to have a distinct coloration. Rather, it is to be a catalyst for an organization whose desired products and services are not clear a priori." What sets the perspective apart from the calculative choice of rational actors and a pure Darwinian process is the intentional design of experimental processes, where the immediate feedback may not be strongly indicative of longer run outcomes of interest. Unlike the conception of rational choice in neoclassical economics, the intentional design is not for a rational design of specific paths forward. The intentional design is constrained by the context in which Mendelian executives operate.

In our paper, we apply the Mendelian perspective to examine the intentional design and the context in which actions are generated and evaluated. The objective of our examination is to extend the two fundamental constructs of the perspective—path-dependence and artificial selection, which are proposed in the perspective as the twin blades of evolutionary dynamics. The core arguments of the theory-based predictions submit that the intentional design efforts of Mendelian executive are constrained and enabled by path-dependence and artificial selection. "Path-dependence is not only a backward-looking constraint, but current actions are enabling of future possibilities" (Levinthal 2021: 13). The artificial selection processes of interest are "the criteria for rewards, capital allocation, and project selection at the various levels of management within the enterprise" (Levinthal

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Table 1 Four external shocks' impact on R4R

External shocks	Cause	Impact on R4R
(1) The shift from oil to natural gas	A drive for lower emissions and higher fuel-to-power energy conversion efficiency	Market demand shifted more toward natural gas as the primary fuel that combustion turbines burn
(2) The shift to global sustainability standards and centralized energy generation	Climate crisis	Market demand shifted toward global sustainability standards for low emissions and high fuel-to-power energy conversion efficiency. Centralized energy generation is associated with the demand for combustion turbines of larger sizes
(3) The shift from fossil-based to sustainable sources of energy and decentralized energy generation	Climate crisis	Market demand shifted toward hydrogen gas as a sustainable source of fuel and decentralized generation as the energy distribution model that eases the burden on the power grid
(4) The disruption to global supply chain caused by the COVID-19 pandemic	Public health crisis	The shock exposed R4R's vulnerability to global supply chain disruptions

A series of four external shocks to electricity generation occurred over a period of decades during which R4R responded to the shifts in market demand. The first shock led to demand shifts toward natural gas as the primary fuel that combustion turbines burn for power generation. The second shock led to demand shifts toward global sustainability standards for low emissions and high fuel-to-power energy conversion efficiency. The third shock led to demand shifts toward sustainable sources of energy and decentralized generation as the energy distribution model that eases the burden on the power grid. The fourth shock was a global supply chain disruption caused by the COVID-19 pandemic

2021: 14). "While the Mendelian executive is capable of enacting an artificial selection environment, this artificial selection environment cannot be fully decoupled from the external selection environment in which the organization operates" (Levinthal 2021: 13). Therefore, we examine path-dependence and artificial selection by matching the theory-based predictions with the patterned principles that we derive from our empirical observations in field research about the selection processes within an organization (e.g., the culling and amplification of strategic initiatives). As we seek to gain a better understanding about how Mendelian executives facilitate a robust and ongoing process of search and discovery in the context of extraordinary, complex and changing environments, the pattern matching allows us to extend the perspective's fundamental constructs.

The focus of our examination is the resource allocation mechanisms that an organization chooses to impose. Our focus is motivated by an intriguing question that Levinthal (2021: 88) posed: "How do organizations distinguish between those initiatives that correspond to climbing towards castles in the sky from those that may be unearthing promising new veins of technological progress and product initiatives? An organization's answer to this key question is reflected in its internal resource allocation process and the extent to which this process is designed to support a multiplicity of selection criteria, while still imposing some degree of selection discipline." As such, we focus on resource allocation mechanisms, specifically the internal processes of redeployment and recombination of resources.

Our field research is conducted in collaboration with a global manufacturer that has been in search of possibly promising ways for the production of sustainable energy. To preserve the anonymity of our field research collaboration partner, we refer to the firm as R4R (the pseudonym means resources for resilience). In collaboration with R4R managers, we track the redeployment and recombination of resources between technology and innovation management and supply chain management over a long period of time during which a series of external shocks to electricity generation took place. R4R has been in the energy industry over several decades during which four external shocks to electricity generation were caused by a drive toward higher fuel-to-power energy conversion efficiency and lower emissions, a climate crisis, and a public health crisis: (1) the shift from oil to natural gas; (2) the shift to global sustainability standards and centralized energy generation; (3) the shift from fossil-based to sustainable sources of energy and decentralized energy generation; and (4) the disruption to global supply chain by the COVID-19 pandemic, a Black Swan event, as summarized in Table 1.

Interviews with managers who have been in charge of the design and delivery of a complex system product at R4R illuminate a persistent association between resource allocation and the firm's stability and functioning through the shocks. Resource allocation decisions are made to re-align continuously two functional level activities: technology and innovation management (product development) and supply chain management (component procurement). We observe empirically an iterated process that re-aligns two interdependent functions—the function of R&D and the function of supply chain—in the allocation of tangible resources (e.g., plants, equipment, and materials) and intangible resources (e.g., human capital, organizational capital, technological capital, and relational capital). The iterated process between

R&D and supply chain management entails technical personnel and testing facility being redeployed and recombined continuously for the purpose of retaining the firm's stability and functioning.

The iterated process that we observe empirically in the allocation of resources between two interdependent functions is consistent with theoretically based predictions about the role of the Mendelian executive. As mentioned earlier, the perspective highlights two fundamental constructs—path-dependence and artificial selection—in characterizing the Mendelian executive as a catalyst and cultivator of possibly promising pathways to not fully knowable futures. These two fundamental constructs, the twin blades of evolutionary dynamics, are consistent with what we observe in our field research. The iterated process that we observe follows two patterned principles in the design of the organization context in which actions are generated and evaluated. The first principle is consistent with path-dependence; the second principle is consistent with artificial selection.

The first principle specifies the interface in product architecture between components of a complex system product. The principle preserves the core component that generates electricity while modularizing the system so the impact of generating and evaluating actions is isolated within components. The exploration of possible adjacent strategic spaces entails experimentation outside the core with different sources of fuel and levels of sustainability. Path-dependence delineates the range of the adjacent possible. As such, the intentional design efforts set the context in which R4R can leverage its existing strengths in the core, while new possibilities can be experimented in modular components. Using resource allocation as a mechanism, managers broker the connection between existing skills and activities into these new possibilities, in the exploration of possible adjacent strategic spaces.

The second principle creates the interface in organizational structures between interdependent functions. The principle sets priorities with strategic initiatives in the absence of necessarily having a clear or definitive point of view as to what constitutes desired pathways. As such, the intentional design efforts situate the context as shifts in market demand that make desired products and services not clear a priori. Artificial selection plays two distinct roles. One role is to map market demand to the culling and reinforcement of strategic initiatives. The other role is to choose contexts in which resource allocation mechanisms are imposed. In essence, the selection is artificial in that the selection rules are the product of conscious choice and not directly the by-product of competitive consequences of market processes. As observed in our field research, experimentations are created to generate and evaluate alternative solutions that may potentially solve the problems arising from shifts in market demand, not solutions for some near instantaneous shifts to equilibrium outcomes. The solutions are generated and evaluated jointly between the firm and its supply chain partners as the technical personnel, from both functions, experiments iteratively with new materials, new tools, and new technologies. The intentional design efforts focus on the design of the context in which alternative solutions are generated and evaluated, rather the design of a particular experiment to conduct at a testing facility.

In addition to showing the consistency between theory-based predictions and field-based observations, our pattern matching contributes to the analytical generalization of a Mendelian perspective, suggesting extensions of the theoretical constructs by enriching path-dependence and artificial selection with boundary conditions in space and time, respectively. We submit an extension of path-dependence by highlighting the interface in product architecture that defines the space of the adjacent possible. The perspective argues that the Mendelian executive is capable of intentional design efforts in order to explore possible adjacent strategic spaces, with path-dependence both constraining and enabling what is possible. Specifically, the property of path-dependence stipulates "the extant population of activities at one point in time is not independent of what that population looked like at an earlier time point" (Levinthal 2022). We extend the argument by specifying a boundary condition regarding the interface in product architecture that constrains and enables the space of the adjacent possible. The Mendelian executive can specify the interface in product architecture thus delineating the space for exploring extant population of activities.

We further submit an extension of artificial selection by highlighting the functional interdependence that defines the temporal synchronization in re-alignment. During the three earlier shocks, the firm was able to absorb environmental disturbance and reorganize in a way that solves the problems while undergoing change so as to retain the firm's stability and functioning. However, the pandemic disrupts the alignment between R&D and supply chain management heavily at a level of severity not observed during the previous three shocks. The severity of disruption exposes the firm's fragility in a complex world, where product development and component procurement are highly interdependent. When component procurement is hampered by a global supply chain disruption, we observe a reduction in the firm's capacity to absorb disturbance as the pandemic disables the iterated process that we derive inductively based on the three earlier shocks. Therefore, retaining a firm's stability and functioning requires a modification to the temporal synchronization between R&D and supply chain for re-alignment in resource allocation. Temporal synchronization serves as a boundary condition in setting the selection rules for resource allocation between interdependent functions.

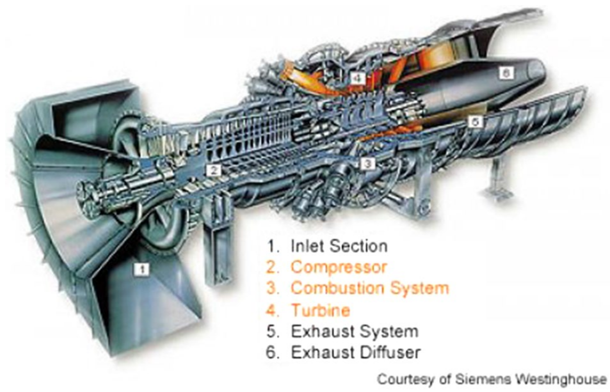


Fig. 1 Diagram of combustion turbine generating electricity from burning fuel

A field-based case study[1]

We have developed a longitudinal case study based on field research. The longitudinal study design enables us to investigate a single case at several points in time as our field research collaboration partner adapts to a changing environment. In our field research, we conducted multiple rounds of on-site interviews with two senior managers who have been in charge of the design and delivery of a complex system product at R4R, a global manufacturer of energy-producing equipment. One of R4R's products is a combustion turbine that generates electricity by converting energy from fuel into power that drives a generator. The fuel can come from fossil-based sources (e.g., oil and natural gas) or sustainable sources (e.g., hydrogen gas). This is a complex system, but its core parts are the following three connected sections, as described by the U.S. Office of Fossil Energy and Carbon Management and shown in Fig. 1.[2]

- The compressor, which draws air into the engine, pressurizes it, and feeds it to the combustion system at speeds of hundreds of miles per hour.
- The combustion system, typically made up of a ring of fuel injectors that inject a steady stream of fuel into combustion chambers, where it mixes with the air. The mixture is burned at temperatures of more than 2000 degrees F. The combustion produces a high temperature, high pressure gas stream that enters and expands through the turbine section.
- The turbine is an intricate array of alternate stationary and rotating aerofoil-section blades. As gas expands through the turbine, it spins the rotating blades. The rotating blades perform a dual function: they drive the compressor to draw more pressurized air into the combustion section, and they spin a generator to produce electricity.

An iterated process of resource allocation between two interdependent functions: R&D and SCM

Managers at R4R explained the interdependence between their R&D and supply chain management (SCM) functions. The synchronized timeline of the two functions' processes is presented in Fig. 2. The timeline on the top of the figure is Technology and Innovation Management department's product development process. The timeline on the bottom of the figure is Supply Chain Management department's component procurement process. Product development process starts with product requirement specifications. The next step in the process is product design specifications. The subsequent five steps (preliminary design, test campaigns, final design including procurement plans, commercialization, field validation, and product) are closely linked with the procurement process. The procurement process has four steps (procurement specifications, preliminary vendor selection, qualification, validation and final vendor selection, and release for manufacturing).

R4R managers provided detailed descriptions that explain each function's processes of allocating nonfinancial resources, as summarized in Fig. 3. Testing facility is the nonfinancial resource that R&D allocates, whereas technical personnel who procures the new components is the nonfinancial resource that SCM allocates. The close link between product development and component procurement is an iterated process of resource allocation between the two functions of R&D and SCM. R&D's new specifications require SCM to procure new materials, new tools, and new technologies from component suppliers. New suppliers need to be identified, validated, and selected. The procured components are the new nonfinancial resources that are combined with other resources in R&D's experimentations with alternative solutions. Alternative solutions may involve new manufacturing methods that incorporate the procured components and require extensive testing. Testing facility and technical personnel are the nonfinancial resources that are jointly allocated to support each iteration of experimentations. When no better solutions are found, another iteration of experimentations begin and the resources of SCM are

[1] Qualitative case studies form the basis for quantitative descriptive models and normative theory building (Brown and Eisenhardt, 1997; Eisenhardt, 1989; Eisenhardt et al., 2016; Feldman, 2004; Whetten, 1989). Theory building from cases also complement computational social science (Bradach, 1997; Brown and Eisenhardt, 1997; Eisenhardt and Bhatia, 2002). We use our field-based case study to enhance a Mendelian's perspective.

[2] https://www.energy.gov/fecm/how-gas-turbine-power-plants-work

Fig. 2 R4R's interdependent functions for designing and delivering a complex system product

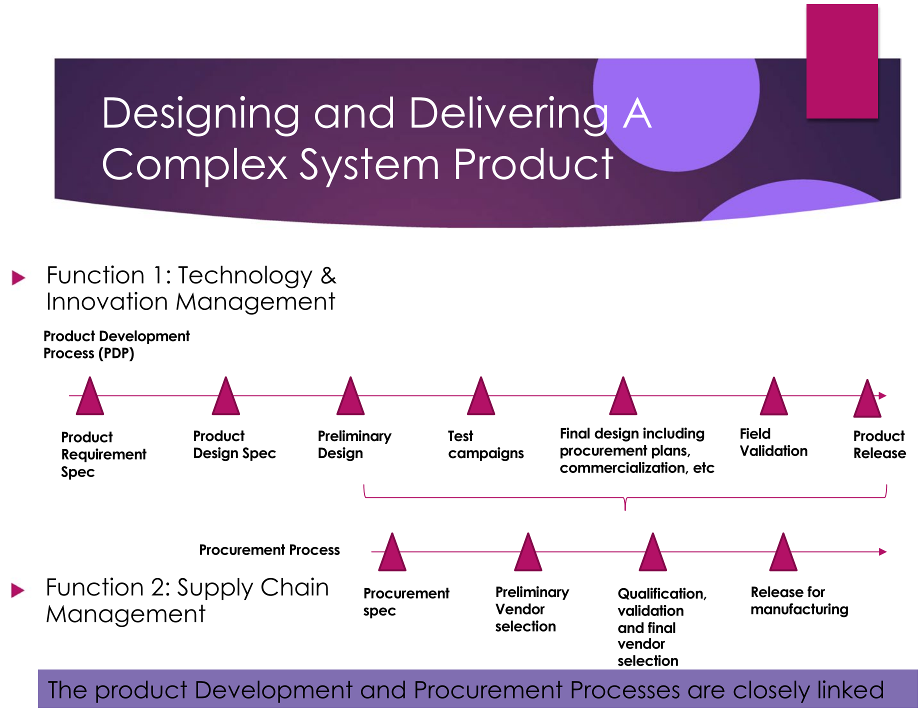
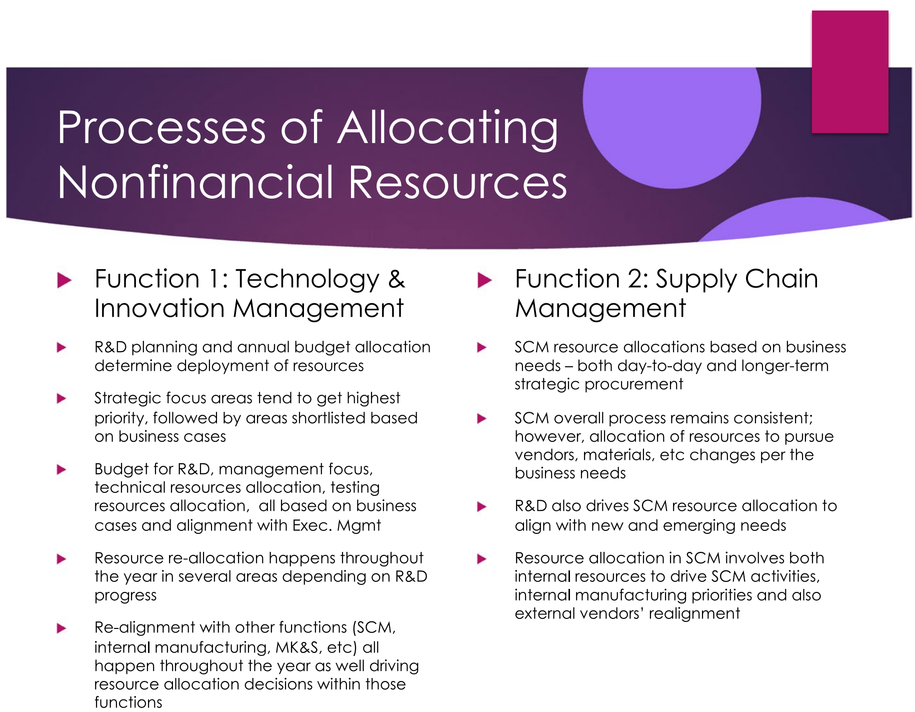


Fig. 3 R4R's processes of allocating nonfinancial resources



redeployed to support this iterated process and temporal synchronization.

R4R managers also provided detailed information that explains how external events drove the allocation of financial and non-financial resources. In R&D, resources were allocated based on priority. Top strategic initiatives have higher priority. Then, allocations were made based on an evaluation of the need and availability of requested resource. In SCM, by contrast, resource allocations and reallocations were driven by the priorities set by R&D as well as other functions, such as operations and manufacturing. The priorities set by R&D thereby create a tight coupling between product development and component procurement.

The interdependence between R&D and SCM is due to not only the tight coupling between the two, but also the aforementioned iterated process of resource allocation. Exogenous shocks such as a drive for lower emissions and higher efficiency with a climate crisis pushing global sustainability standards triggered major shifts in market demand. Meeting the demand shifts was set as a priority by the R&D function. Managers at R&D set new specifications for product requirement as the first step in the product development process. Technical personnel such as design engineers was redeployed from their current assignment to their new assignment to create new specifications for product design. R4R's combustion system had to be redesigned based on new specifications, to meet the demand shifts for natural gas as the fuel and reduced emissions as the sustainability standard. R4R's turbine and compressor had to be redesigned as well. The new specifications required different blade geometries and different materials to meet the demand shifts for higher fuel-to-power efficiency as the sustainability standard and more electricity output per unit time as the performance standard.

The specification requirements from R&D drove SCM's procurement of new materials, new tools, and new technologies from component suppliers. The procured components were used in each iteration of experimentations to explore alternative solutions for meeting the demand shifts. For example, to increase fuel-to-power efficiency, metals and advanced materials that can withstand higher temperatures were new materials that were procured. As another example, three-dimensional (3D) printing was a technology that was procured to more quickly develop components that have intricate geometries.[3] 3D printing, which is additive manufacturing, is superior to conventional methods, such as casting, because it increases R4R's ability to develop components faster and with higher yield rates.

Temporal synchronization is a key aspect about the degree of interdependence between R&D and supply chain. By contrast, asynchrony means that, while the planning of resource allocation is synchronized between the two functions, the timing at which multiple types of resources are redeployed can be asynchronous in execution. Continuing with the example of 3D printing as mentioned earlier, this technology can be redeployed asynchronously to provide distributed, on-demand production for various component prototypes, not necessarily synchronized with the current top-priority requests imposed by R&D. The asynchronous production can build inventory that may buffer the disruptions to supply chain. Procuring the 3D printing technology is a form of vertical integration that could protect the firm's access to key components. This approach of procuring technological resources as a way to help the firm restore its stability and functioning more quickly is different from the traditional approach of adding redundancy in supply chain (e.g., using multiple suppliers across multiple geographic regions and through multiple channels to source the same component) or using long-term supplier contracts to secure key components.

Resource allocation and experimentation to address demand shifts

At R4R, resource allocation decisions were made continuously to address the demand shifts caused by external shocks. R4R managers explained in detail how resources are allocated to address demand shifts using two specific examples: (1) the demand shift toward hydrogen; and (2) the demand shift toward decentralized generation. These two demand shifts are the current challenges about which R4R managers are designing experimentations to address.

The demand shift toward hydrogen gas as a sustainable source of fuel requires the combustion turbine to burn hydrogen gas. Hydrogen gas is a sustainable source of fuel because it can be produced from water using surplus renewable electricity generated from solar or wind. Whereas the availability of solar and wind fluctuates with the weather, the availability of hydrogen gas is more stable because its inventory can be built and reconverted into electricity on demand, with no carbon emission. However, hydrogen gas is a highly reactive fuel, so it must be stored, transported and used safely. In addition to the economic and safety concerns, a major technical challenge of burning hydrogen gas is that its high flame speed threatens to suck the flame back, which may destroy the burner. To protect the burner, the speed of the fuel and air mixture upstream in the burner has to be higher than the flame speed of hydrogen. The technical challenge is how to adjust the fuel injection so as to increase the hydrogen ratio in the fuel mix. New technologies such as 3D printing are used to adjust the design inside the burner while keeping the same interfaces that the burner has with the other components of the combustion turbine (e.g., adjusting the inside without changing the burner's exterior). Isolating the experimentations with 3D printing to key components while keeping the overall complex system's functional design unchanged is how the product maintains its stability and functioning.

The attractiveness of using hydrogen gas as a sustainable source of fuel, as demonstrated by the U.S. Department of Energy's turbine program, is that hydrogen and syngas fired gas turbine combined cycle plants are likely to achieve

[3] https://www.hydrogen.energy.gov/pdfs/htac_nov14_14_marshall.pdf Additive manufacturing,
commonly known as 3D Printing, is a set of emerging technologies that fabricate parts using a layer-by-layer.
technique, where material is placed precisely as directed from a digital file.

fuel-to-power conversion efficiencies of 60% or more. In comparison, a simple cycle gas turbine can only achieve between 20% and 35%. Iterations of experimentations on how to increase the hydrogen ratio in the fuel mix toward 100% are on-going. The hydrogen gas currently used in combustion turbines is called "brown" hydrogen, because the hydrogen gas is mixed with waste gas from industrial processes involving fossil fuels. Therefore, the need to reduce harmful emissions remains.

As R&D's experimentations with 100% hydrogen gas as the fuel source continue to iterate, SCM realigns its resources to support for R&D's needs for new components. The new component can be reused and recombined with other resources in future experimentations. The two aforementioned examples that involve 3D printing are concrete outcomes of SCM's procurement process that supports additive manufacturing, a new technology required by R&D. Resources, both financial and nonfinancial are reallocated and redeployed because the selection criteria, boundary conditions, materials and skills for additive manufacturing are different from the requirements of experimenting with different technologies.

The demand shift toward decentralized generation as the energy distribution model that eases the burden on the power grid requires a revised focus on smaller combustion turbines. The demand for large turbines has been in decline, because smaller ones allow for decentralized generation. The energy distribution model has shifted from centralized generation toward decentralized generation, so as to ease the burden on the power grid. The shift toward decentralized generation also reduces a geographical area's vulnerability to severe disruptions in energy transportation through the power grid. This shift toward decentralized generation coincides with the shift toward hydrogen gas as the fuel. The combustion turbines that are being experimented with hydrogen gas as the primary fuel are small to medium in size, because the aforementioned safety concerns discourage the storage and transportation of large amounts of hydrogen gas. As such, R&D required new materials, tools, and manufacturing methods for SCM to procure so as to conduct experimentations for decentralized generation with combustion turbines of smaller sizes.

Resource allocation as a mechanism for stability and functioning

Our field-based case study connects the processes shaping the allocation of physical, technological, and human resources to the firm's stability and functioning. Structured interviews with R4R managers illuminate a persistent association between resource allocation and the firm's stability and functioning. The firm's stability and functioning are retained by the aforementioned iterated process of resource allocation—testing facility and technical personnel being redeployed and nonfinancial resources being recombined continuously through iterations of experimentations. The core parts of the complex system product are preserved. The experimentations were isolated in the new components (new materials, new tools, and new technologies) that do not disturb the stability and functioning of the product as well as those of the firm.

R4R used the same process for resource allocation in its responses to shocks. Over a period of decades, four external shocks to electricity generation occurred as a result of a drive for lower emissions and higher efficiency, a climate crisis, and a public health crisis. When the three earlier shocks occurred, R4R was able to absorb the disturbance and reorganize in a way that solved the problems arising from the shocks while undergoing change so as to retain the firm's stability and functioning. Yet, the fourth shock, a global supply chain disruption caused by the COVID-19 pandemic, interrupted the alignment between R&D and SCM, thereby severing the mechanism via which resource allocation was connected to the firm's stability and functioning.

Severing the resource allocation mechanism exposed the firm's fragility. The Black Swan event that surprised R4R managers had a more immediate impact on the tactical side of the firm. SCM was severely impacted, whereas there was not much of an impact on R&D. SCM process was stable, but the functioning of the SCM team was negatively affected by the global supply chain disruptions caused by the COVID-19 pandemic. The public health crisis disrupted R4R's process of resource allocation by restricting component procurement. While there were numerous factors that disrupted R4R's stability and functioning during the COVID-19 pandemic, the disruption only affected supply chain, not R&D. R&D was able to continue after a swift adjustment for work-from-home arrangements. When the function of component procurement was hampered, the firm's capacity to absorb disturbance was reduced.

Resources for resilience

Our case study adds to the research on the purposes and processes of resource allocation by examining how a firm retains its stability and functioning in complex and changing environments. More broadly, our study highlights resource allocation as a mechanism for retaining stability and functioning with which the Mendelian executive facilitates a robust and ongoing process of search and discovery. While resource allocation as a mechanism for retaining stability and functioning is observed in our case study, if additional case studies provide similar patterns, the iterated process of resource allocation may explain the phenomenon of the

Mendelian executive more precisely. Below, we suggest additional case studies for further examination in the future.

Research on the purposes of resource allocation has covered response to digital technology (Gilbert 2005), renewal of the firm (Danneels 2002, 2007), transition of technological competence (Danneels et al. 2018), innovation performance (Klingebiel and Rammer 2014), and financial performance (Lovallo et al. 2020). Resource allocation has been connected to general purposes of improving innovation and financial performances (Klingebiel and Rammer 2014; Lovallo et al. 2020) when there are changes in the environment (Danneels 2002; Danneels et al. 2018; Gilbert 2005), as summarized in Table 2. For example, one purpose is to respond to discontinuous change in the environment, such as the threat of digital publishing to newspaper firms' revenues, profits, and survival (Gilbert 2005).

In addition to the research on the purposes of resource allocation, the research on the processes of resource allocation have culminated several prominent models describing how resources are committed to emerging markets (Christensen and Bower 1996), new businesses (Noda and Bower 1996), new customers (Danneels 2007), new product features (Ethiraj et al. 2012), new locations (Natarajan et al. 2019), and breakthrough inventions (Vinokurova and Kapoor, 2020). Each model focuses on specific features of the environment, specific contexts of the firm, or specific resources of the firm, as summarized in Table 3. Specific features of the environment include the rate of technical progress exceeding the performance demanded in a market (Christensen and Bower 1996). Specific contexts of the firm include the structural and strategic contexts of a large multi-business corporation, where, to survive, bottom-up strategic initiatives had to compete to secure scarce resources and top managers' attention (Noda and Bower 1996). Specific resources of the firm include a fungible technology that can be leveraged across many applications, products and markets, as well as the extraction of additional value from under-utilized resources (Danneels 2007). Further examination of the resource allocation mechanism in extraordinary, complex and changing environments may richly extend and enhance a Mendelian perspective.

Path-dependence and artificial selection in an iterated process of resource allocation

Our case study that has revealed an iterated process of resource allocation is motivated by Levinthal's (2021: 88) proposition that was mentioned in the introduction: "How do organizations distinguish between those initiatives that correspond to climbing towards castles in the sky from those that may be unearthing promising new veins of technological progress and product initiatives? An organization's answer to this key question is reflected in its internal resource allocation process and the extent to which this process is designed to support a multiplicity of selection criteria, while still imposing some degree of selection discipline." R4R's iterated process of resource allocation has implications for such a proposition in light of the perspective's core arguments.

The implications are threefold. First, there is consistency between theory-based predictions and field-based observations. The intentional design efforts that we observe in our field research and derive from the empirical observations in the context of extraordinary, complex and changing environments are indeed constrained and enabled by path-dependence and artificial selection. Path-dependence constrains and enables the exploration of possible adjacent strategic spaces. R4R's modular product architecture, as a source of path-dependence, delineates the set of possible initiatives, which is a function of the set of existing initiatives and resources at R4R's disposal. Specifically, R4R managers leverage the existing strengths in the core component of the complex system product while isolating the experimentation in adjacent components. Outside the core component, R4R managers design experimentations to explore different sources of fuel and levels of sustainability when market demand shifts. Artificial selection also constrains and enables the exploration of possible adjacent strategic spaces. R4R managers design selection rules that are the product of conscious choices restricting the context in which alternative solutions are generated and evaluated. The exploration is restricted to adjacent strategic spaces, where alternative solutions may potentially solve the problems arising from shifts in market demand. At the same time, the exploration with new materials, new tools, and new technologies enables the generation and evaluation of alternative solutions in contexts that involve R4R and its supply chain partners jointly.

The second and the third implications are analytical generalizations of a Mendelian perspective. Findings from our case study suggests an extension of the path-dependence construct by highlighting a boundary condition. The boundary condition is the interface in product architecture that constrains and enables the space of the adjacent possible. Whereas the perspective currently stipulates that "Path-dependence is not only a backward-looking constraint, but current actions are enabling of future possibilities" (Levinthal 2021: 13), we extend the perspective by suggesting that the interface in product architecture could be a factor that delineates the space for exploring the adjacent possible.

Findings from our case study also suggests an extension of the artificial selection construct by highlighting a boundary condition. The boundary condition is the temporal synchronization that constrains and enables the design of selection rules for resource allocation between interdependent functions. Whereas the perspective currently maintains that the artificial selection processes of

Table 2 Purposes of resource allocation

Intended purposes	Observed means of allocating resources	Research design
Response to discontinuous change via expanding resource commitments, including financial expenditures, headcount, management time and effort	Overcoming two types of resource rigidity: one stemming from resource dependence and the other from incumbent position reinvestment incentives	Gilbert (2005) compared eight cases as a series of experiments to study the response of newspaper firms to digital publishing, examining why established newspaper firms failed to invest financial and attention-based resources in digital publishing
Organizational innovation and renewal in a business environment characterized by fast changes in customers, technologies, and competition	Renewal of firm competences in changing environments is achieved by allocating resources for developing and marketing new products that expand the competence base of the firm, which in turn enables further new products	Danneels (2002) conducted field research in five high-tech firms of varying age, size, and level of diversification
Transition of technological competence over time, whereby an emerging competence overtakes, and ultimately displaces, the incumbent competence	Technological competence becomes socially embedded in a firm over time as it is legitimized, backed by powerful agents, and supported by resource allocation	Danneels et al. (2018) developed a historical case study of an office products firm
Performance outcomes of innovation project portfolios (increases in new product sales)	The choice of resource allocation strategy—allocating resources widely to a broad range of innovation projects and selectively at later stages of the innovation process	Klingebiel and Rammer (2014) empirically tested predictions with survey data
Firm profitability	Reallocating capital across business units	Lovallo et al. (2020) studied the change in year-to-year financial resource allocation flow between business segments in a data set of several thousand firms spanning 18 years
The firm's stability and functioning	The firm's stability and functioning are retained by an iterated process of resource allocation between R&D and SCM in a way that preserves the core of a complex system product while modularizing the system to isolate the impact of experimentations	The current study conducted field research in collaboration with a global manufacturer, which has been in the energy industry over several decades during which four external shocks to electricity generation were caused by a drive for lower emissions and higher efficiency, a climate crisis, and a public health crisis

Table 3 Processes of resource allocation

Descriptive models	Research design
The allocation of resources in technological innovation as shaped by the demands of a firm's customers	Christensen and Bower (1996) developed a case study of the world disk drive industry, showing that, because the rate of technical progress can exceed the performance demanded in a market, technologies which initially can only be used in emerging markets later can invade mainstream ones, carrying entrant firms to victory over established companies
An iterated process of resource allocation via committing resources to new businesses. The Bower-Burgelman model describes how bottom-up strategic initiatives compete for scarce corporate resources and top managers' attention to survive within the corporate contexts	Noda and Bower (1996) conducted a comparative analysis of a single business across multiple firms, tracing the efforts of multiple firms in response to the same market opportunity. The analysis contrasts two of the seven Bell regional holding companies in their experience with developing and expanding the business of wireless communications between 1983 and mid 1994
The processes of resource allocation and resource transformation inhibited technology leveraging, shaped by the presence of a competence to serve current customers (a customer competence trap) and the lack of a competence to gain access to new customers (a marketing competence gap)	Danneels (2007) documented a longitudinal case study of a firm that successfully applied a fungible technology to products for its served market, but was unable to tap its considerable potential in new markets
The allocation of financial resources within a firm entails a process of determination, comparison, and selection among multiple investment alternatives, taking place across organizational levels of the firm, and influenced and constrained by the external context in which the firm is situated	Sengul et al. (2019) provided a structured review of the research on intra-firm capital allocation in multiple disciplines, including strategic management, accounting, operations, corporate finance, and financial economics
Two processes: (1) Searching across the organization for more favorable evaluation criteria leveraged the heterogeneity of evaluation criteria across the different organizational units. (2) Shaping the evaluation criteria to help attract resources required the presence of evaluative uncertainty with respect to the appropriate criteria for evaluating breakthrough inventions	Vinokurova and Kapoor (2020) used historical case studies of three breakthrough inventions at Xerox-office workstations, personal computers, and laser printers, illustrating how inventors in a large firm navigated multiple evaluation criteria across different organizational units to attract resources so as to commercialize the inventors' breakthrough inventions
The process of evaluating customer requests for new product features highlights how firms respond to customer requests for incremental product innovations, and how these responses change when the requested innovation is complex	Ethira et al. (2012) used large sample empirical analyses combined with detailed qualitative data drawn from interviews, revealing the importance of organization structures, competitive pressures, and incentives for resource allocation processes
The involvement of middle managers in the decision making about resource allocation, focusing on how rewards and controls have different associations with resource allocation depending on the level of managers involved in decision making. Higher rewards arising from uncertainty about employee income growth and lower controls based on monitoring increase resource allocation most strongly when middle managers are more involved in decisions	Natarajan et al. (2019) studied the allocation of ATM and bank branch (which locations and how many) in Indian commercial banks from 2011 to 2014, a high-growth environment undergoing rapid technological transformation and evolution of social goals
An iterated process of resource allocation—technical personnel and testing facility being redeployed and recombined continuously between R&D and SCM—underlies the experimentations for solutions that may potentially solve the problems arising from external shocks. The solutions are generated and tested jointly between the firm and its supply chain partners as the technical personnel, from both functions, experiments iteratively with new materials, new tools, and new technologies	The current study derives inductively an iterated process of resource allocation between two interdependent functions: R&D and SCM

interest are "the criteria for rewards, capital allocation, and project selection at the various levels of management within the enterprise" (Levinthal 2021: 14), we extend the perspective by suggesting that the temporal synchronization between interdependent functions for re-alignment in resource allocation could involve selecting supply chain partners outside the enterprise.

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