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RESEARCH ARTICLE

The microfoundations of an operational capability in digital manufacturing

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Abstract

This article seeks insights into how individuals, processes, and structures interact to form the microfoundations of an operational capability in digital manufacturing. Using a knowledge-based theory lens, we develop an empirical framework that explains how structures and processes encourage individuals to interact and share knowledge, and through these interactions, operating routines and operational capabilities emerge. The model is further refined using data collected from 40 interviews, steering committee meetings and participant observations at a high technology aerospace company. We find that discrete technologies, used in one component or subassembly, can be developed within authority-based hierarchies using rigid new product development processes. We also find that whole system technologies that affect multiple aspects of the final product require flexible processes and consensus-based hierarchical structures. Consensus-based structures include centers of competence, which provide individuals the freedom to "learn through failure" and develop flexible ad hoc problem solving processes. Such flexible processes encourage individuals to learn from their mistakes and share new knowledge on a repetitive basis, leading to the emergence of operating routines. The paper contributes to the knowledge-based view by empirically demonstrating how different types of new technology development programs, be they for discrete or whole system technologies, may benefit from different configurations of flexible/rigid processes and authority-based/consensus-based structures.

KEYWORDS
3D printing, additive manufacturing, capabilities, digital manufacturing, microfoundations, routines

1 | INTRODUCTION

In 2015, additive manufactured goods represented less than 1% of all products made in the United States (UPS, 2018). Three years later, *Forbes* magazine found that additive manufacturing contributed to just 0.04% of global manufacturing output (*Forbes*, 2018). McKinsey and Co. suggests the reason for this slow uptake is due to companies not having a clear roadmap on how to develop additive manufacturing within their operations (McKinsey and Co., 2017). We adopt a knowledge-based view (KBV) theoretical lens to understand this issue, exploring how one leading technology firm developed operational capabilities in the use of additive manufacturing that led to improved technological performance.

Operational capabilities refer to the repeated and reliable performance of an activity (Helfat & Winter, 2011) and represent a firm's intended or realized operational strengths (Ferdows & De Meyer, 1990; Flynn & Flynn, 2004; Flynn, Schroeder, & Flynn, 1999). Operational capabilities are created by developing operating routines, which form the basis for these capabilities and subsequently become established over time (Peng, Schroeder, & Shah, 2008). The operations management literature has several examples of how firms have developed operating routines that eventually form operational capabilities (see Adler, Goldoftas, & Levine, 1999; Anand, Gray, & Siemsen, 2012; Peng et al., 2008).

The focus of our analysis is at the microfoundational level (Felin, Foss, Heimeriks, & Madsen, 2012) of the firm, where human interactions constitute the primary source of knowledge development and knowledge transfer. The notion of microfoundations stems from the KBV, where knowledge is positioned as a firm's most valuable resource and individuals act as the locus of that knowledge (Grant, 1996a; Nonaka, 1994). The microfoundations of organizational routines and capabilities refer to the “interaction” effects that occur between individuals, processes, and structures, and that lead to the emergence of macro-level outcomes (Felin et al., 2012 p. 1353). We adopt this theoretical perspective to answer the following research question: *What role do individuals, structures, and processes play in the development of an operational capability in additive manufacturing*?

In addressing this question, we conducted an in-depth case study of a high technology aerospace firm, using the company's additive manufacturing development program as the unit of analysis. Additive manufacturing's development provides a rich context to study how individuals, processes, and structures interact to form operational capabilities. The novelty and unique properties of additive manufacturing require individuals from diverse backgrounds to work around hierarchical structural boundaries and form consensus driven cross-functional teams to enable them to integrate the new technology development process into the focal firm. This case analysis created a unique opportunity to observe how microlevel interactions aggregated into operating routines and led to the emergence of a macrolevel operational capability in digital manufacturing. Data were collected using semistructured interviews, steering committee meetings, and participant observation; data were objectively verified using company documentation, following methods aligned with unobtrusive measures (Webb et al., 1999). By gathering empirical data to study this phenomenon, we respond to the call of Felin et al. (2012) to explain the origins of routines and capabilities by analytically focusing on three primary microfoundations: (a) individuals, (b) processes and interactions, and (c) structures.

The remainder of the article is divided into four sections. In the next section, we use a theory-building approach to explain how individuals, processes, and structures interact, and how such interaction leads to the emergence of operating routines and operational capabilities. Section 3 provides a justification for the research design, data collection, and analysis methods. Section 4 presents the findings from the case. The final section compares the empirical evidence to the existing literature to arrive at a framework of the microfoundations of an operational capability in digital manufacturing. The article concludes by outlining the study's contribution to theory and managerial practice and proposing potential areas for future research.

2 | LITERATURE REVIEW

The foundations of competitive advantage research are linked to the idea that the unique information possessed by a firm (Barney, 1986), combined with the ability to unlock this information in an efficient and effective manner, are critical to an organization's growth. Others suggest it may simply be attributable to luck (i.e., being in the right place at the right time) (Denrell, Fang, & Winter, 2003; Winter, 2013). The idea that firms possess superior knowledge or information is recognized as the aggregate product of individual behaviors, as information and knowledge is created from an aggregation of individuals' knowledge and experiences within the firm (Felin & Hesterly, 2007; Nelson & Winter, 1982).

Traditionally, theories of strategic factor markets (Barney, 1986) and theories of the firm (Williamson, 1981; Williamson, 1987) have focused on the formation of strategy by a single actor, namely the firm. This level of “macro” analysis offers a limited explanation of why some firms are better able to succeed than others. The concept of microfoundations (Felin & Hesterly, 2007) provides a more granular context for understanding how capabilities are formed, how individuals act within organizations, as well as the specific roles of individuals in creating organizational capability (Barney & Felin, 2013 p. 149). A microfoundational level of analysis is not only concerned with skills, ability, capability, and knowledge, but also how the aggregate capability is created, with a particular focus on organizational design, structure, and process (cf.Barney & Felin, 2013 ; Felin et al., 2012). Exploring how the constituent microfoundational elements of organizational design, structure, and process interact with one another can explain how capabilities are created (Barney & Felin, 2013; Felin et al., 2012). Research suggests that poorly designed organizations with misaligned structures and siloed processes may lead to unrealized operational capabilities that remain dormant and may even lead to an organization's demise (cf. Foss, 2003). Using the KBV, we next explore how operational capabilities may be created within the microfoundations context. We are explicitly interested in responding to scholars (Greve, 2013; Harper & Lewis, 2012) that describe the link between macro (strategic capability) and the microfoundational construction of capabilities.

2.1 | Operational capabilities

In the context of the KBV of organizational design, an operational capability is a broad functional capability that consists of activity-related capabilities; for instance, these might include a manufacturing capability, a materials management capability, and a process and product engineering capability (Grant, 1996a). Operations management (OM) scholars have long argued that manufacturing firms do not need to trade-off one capability for another but can compete on different objectives simultaneously (Ferdows & De Meyer, 1990; Flynn et al., 1999). There is general agreement that once operational capabilities are in place, the firm will achieve performance benefits (Ferdows & De Meyer, 1990; Flynn et al., 1999; Flynn & Flynn, 2004).

Recently, scholars have sought to identify operational capabilities derived from digital manufacturing technologies (Ford & Despeisse, 2016; Holmström, Holweg, Khajavi, & Partanen, 2016; Roscoe & Blome, 2019). Digital manufacturing integrates the design-to-manufacturing process using digital tools; these include computer-aided design and manufacturing (CAD/CAM) (Jin, Curran, Burke, & Welch, 2012). Of particular interest is the emergence of additive manufacturing capabilities; by building products additively, companies can reduce costs by removing redundant steps from the production process including tooling, line-changeovers, and subassemblies (Berman, 2012; Holmström et al., 2016). Additive manufacturing can also reduce costs by using fewer raw materials and generating significantly less waste when compared to conventional manufacturing processes (Ford & Despeisse, 2016). Furthermore, the technology can shorten global supply chains by allowing companies to print customized products closer to the consumer, reducing inventory, and enhancing responsiveness to customer demand (Holmström, Liotta, & Chaudhuri, 2017; Roscoe & Blome, 2019). Additive manufacturing is purported to improve an operation's flexibility; it does so by opening up new design spaces, allowing novel forms to be imagined and created (D'Aveni, 2015). It stands to reason, then, that a capability in additive manufacturing may allow a firm to realize performance benefits, be it flexible production methods, shorter lead times, enhanced quality and/or lower manufacturing costs.

A related question to deployment of additive manufacturing involves how organizations should integrate such new technologies into their operating routines? OM scholars have made significant progress in identifying the ways in which operating routines support the emergence of operational capabilities (Adler et al., 1999; Peng et al., 2008; Swink, Narasimhan, & Wang, 2007). Operational capabilities emerge from the bundling together and deployment of operating routines (Peng et al., 2008). Operating routines involve the execution of known procedures for the purpose of generating current revenue and profit (Zollo & Winter, 2002 p. 341). They are fixed, and by repetitively executing groups of operating routines over time, static operational capabilities emerge (Peng et al., 2008). Adler et al. (1999) found that standardized problem solving, fixed changeover procedures, and a reflection-review routine allowed companies to switch between routine production roles and nonroutine continuous improvement tasks, creating both flexibility and efficiency in the operation (Adler et al., 1999). Swink et al. (2007) noted that product and process technology integration routines were associated with manufacturing plants' capability to quickly and efficiently bring new products to full-scale production. Peng et al. (2008) determined that operational improvement capabilities emerge from the bundling together of continuous improvement routines, process management routines, and leadership involvement.

This discourse provides a basis for exploring how the bundling together and deployment of multiple interrelated operating routines leads to the emergence of operational capabilities. What is less apparent from the OM literature is how microlevel interactions are aggregated to become embedded as operating routines. The purpose of this article is to address this gap in the research by determining how interactions between individuals, structures, and processes lead to the emergence of operating routines.

2.2 | The microfoundations of operating routines and operational capabilities

The question of how to link micro factors with macro capabilities remains a topic of debate in management strategy, organizational learning, and behavioral sciences research (e.g., Felin et al., 2012; Harper & Lewis, 2012; Raub, Buskens, & Van Assen, 2011). In the last decade, scholars have identified the need for insights on collectives, including areas such as group cohesion and knowledge (see Kozlowski & Chao, 2012). Eisenhardt, Furr, and Bingham (2010) initiated the debate on the role of structure and the development of simple rules in dynamic environments. Barney and Felin (2013) introduced the idea of social aggregation–specifically how organizations can link macro and microfoundational activities with routines and capabilities. Building on this work, we begin by first exploring the role of the individual within the collective, and then proceed to examine processes and facilitating structures and their role in unlocking capability.

Routines emerge when individuals, working as a collective, develop sequential patterns of interaction that permit the integration of their specialized knowledge without the need for communicating that knowledge (Grant, 1996a). Our emphasis here is on the collective activity, its constituent parts and social interactions, as opposed to extrapolations of the collective itself (Barney & Felin, 2013). The KBV is useful in this regard, as a key assumption of this framework is that knowledge is created by individuals (Grant, 1996a, 1996b; Nonaka, 1994). When individuals enter a focal organization, they carry with them pre-existing knowledge from other organizations and apply this knowledge in their new roles (Grant, 1996a; Grant, 1996b). Over time, individuals accumulate knowledge on-the-job through training, peer observation, and experiential learning (Felin et al., 2012; Grant, 1996b). In the new product development (NPD) process, for instance, individuals accrue specialist knowledge in a productive task and will draw on this knowledge to simplify the task until it can be executed repeatedly by other individuals (Grant, 1996b). For example, when building an engine, a manager may provide employees with step-by-step instructions on how components must be assembled and in what order. When employees repeat the task multiple times, their specialist knowledge becomes embedded in the production process and engine assembly becomes a routine task.

However, microfoundations are not only about individuals per se: they are also concerned with the level and types of interactions between individuals within the organization, which eventually evolve into a collective (Whetten, Felin, & King, 2009). Interaction is defined as instances when two or more individuals engage with one another using verbal and non-verbal social mechanisms (Cousins, Handfield, Lawson, & Petersen, 2006; Cousins & Menguc, 2006; Felin & Hesterly, 2007). Mechanisms are defined as a natural or established instrument or activity by which something takes place or is brought about; it can be formal or informal in nature (Cousins et al., 2006). When individuals interact with one another formally and informally in their daily roles, they are provided with the opportunity to share ideas and information. Formal socialization mechanisms refer to designated structures created to communicate expectations and share useful knowledge between individuals, such as regularly scheduled meetings, conferences or staff events (Cousins et al., 2006). Informal socialization mechanisms are less structured and refer to impromptu chats in the hall or after hours social engagements; activities that help to build trust between individuals and facilitate the sharing of ideas (Cousins & Menguc, 2006) These interactions are not simply additive, but can evolve into complex forms, and result in synergistic outcomes that are not evident in the context of a single individual's knowledge (Barney & Felin, 2013).

From a strategic perspective, the literature on talent and mobility is relevant as it provides an additive perspective on organizational design. In certain contexts, the performance of an organization can be directly attributed to the talents of particular people within the organization; conversely, individuals (and collectives) can be constrained if the organization's processes and structures act to inhibit formal and informal socialization mechanisms (see Barney & Felin, 2013; Felin & Hesterly, 2007). Microfoundations therefore not only recognize the importance of the individual, but more importantly how individuals interact within the structures and processes of the organization's design.

2.3 | Process design determines individual interactions

A process is defined as a sequence of interdependent events (Felin et al., 2012 p. 1362). Processes act as integrating mechanisms by facilitating the amalgamation of different organizational elements including individuals, teams, departments, or cross-functional knowledge resources (Henderson & Clark, 1990; Hoopes & Postrel, 1999). Processes can be rigid or flexible (Felin et al., 2012), and the design of processes can significantly determine the pattern of individual interactions. Rigid processes refer to sequences of events that are organized and controlled, where individuals have assigned roles and responsibilities (Felin et al., 2012). An example of a rigid process is the NPD process, which occurs when designers, research and development (R&D) experts, and engineers interact to combine their specialist knowledge to develop new variations of a product (Clark & Fujimoto, 1991). The NPD process encourages individuals to interact with people in different parts of the business, meaning that an individual's understanding and decision-making abilities will no longer be bounded by a particular job role (Simon, 1991).

Flexible processes refer to a sequence of events that can be modified by the individuals involved in order to arrive at a desired end (Felin et al., 2012). Flexible processes include technology testing, where R&D experts experiment with the development of new technologies using a process of trial-and-error learning (Hoopes & Madsen, 2008), and ad hoc problem solving (Winter, 2003). For example, Lockheed Martin's “skunk works” process gives individuals the freedom to experiment with and develop new technologies and product designs. We note that not all such experiments are successful, which is indeed a required component of learning. In fact, learning through failure is an important part of the scientific theory-building process (Lee, 1999). The interaction between individuals and processes creates a self-reinforcing cycle where individuals learn through their failures and, by applying this newly acquired knowledge, continue to improve the process. This role of processes in the integration of individuals is depicted in Figure 1.

Figure 1 suggests that processes act as integrating mechanisms by bringing individuals together to share knowledge. Furthermore, it is argued that the interaction between individuals allows for the accumulation of knowledge that, when applied through experiments, can improve the process. Figure 1 also suggests that organizational structures play an important role in determining the microfoundational nature of how individuals interact and how often such interactions occur.

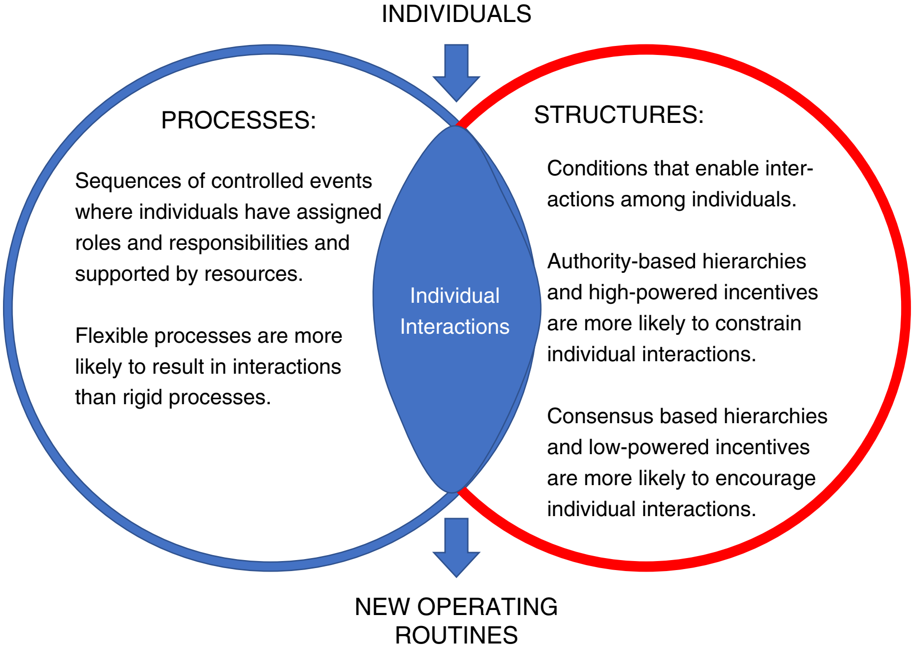

FIGURE 1 Interactions between individuals, processes, and structures [Color figure can be viewed at wileyonlinelibrary.com]

2.4 | Organizational structure design determines individual interactions

Microfoundations provide a methodological lens to explore the power of looking at lower-level constituent units when explaining higher levels of analysis. The exploration of microfoundations requires us to systematically examine the origins and nature of microlevel constructs: how choices and interactions create structure, the behavior of individuals within structures, and the role of individuals that shape organizational structures over time (Chwe, 2013). Rather than taking structural and macro factors for granted, the goal of microfoundational analysis is to examine their origins and evolution by looking at how microfactors emerge as a function of individual choices and social interactions. In a sense, microfoundation analysis shifts the causal arrow from macro → micro, to micro → macro analysis (Barney & Felin, 2013).

Organizational structures are defined as conditions that enable or constrain individual and collective interactions within an organization (Felin et al., 2012 p. 1364). The basic structure for organizing complex social activity involves hierarchies (Grant, 1996b). Organizational hierarchies can be understood as either authority based or consensus based (Nickerson & Zenger, 2004). An authority-based hierarchy relies on the centralization of decision-making to economize on the transmission and handling of knowledge (Arrow, 1974). In an authority-based hierarchy, a senior manager invests in understanding critical knowledge interactions and then composes suitable heuristics to guide the search for solutions (Nickerson & Zenger, 2004). To create new knowledge, a senior manager defines a relevant and pressing problem in the business that, if solved successfully, yields new knowledge (Nickerson & Zenger, 2004). Some problems are relatively noncomplex and decomposable and can be subdivided into subproblems that are solvable with the specialized knowledge of an individual (Simon, 1962). The solving of noncomplex problems is suited to an authority-based hierarchy because senior managers can define the search criteria and nominate an individual with the appropriate specialized knowledge to solve the problem (Nickerson & Zenger, 2004).

Other problems are highly complex and nondecomposable. Solving such problems requires interaction between a wide variety of different knowledge sets from around the organization (Felin & Zenger, 2014). For example, the development of an innovative technology such as Additive Manufacturing is a highly complex problem that requires the specialized knowledge input from individuals in procurement, materials, design, engineering, operations and manufacturing. An authority-based hierarchy does not promote the horizontal communication channels needed to support such knowledge sharing amongst peers (Nickerson & Zenger, 2004). Instead, the solving of highly complex problems is better suited to a consensus-based hierarchy which emphasizes knowledge sharing across diverse knowledge sets (Nickerson & Zenger, 2004). Holweg and Pil (2008) argue that technological change, such as new IT systems, can facilitate the horizontal exchange of information and the locus of individual power. Unlike an authority-based hierarchy, a consensus based hierarchy involves having individuals collectively agree on a path of search and create a commonly shared language that integrates their specialized knowledge (Arrow, 1974). Creating a shared identity within the organization lowers the cost of communication and establishes rules of coordination that influence the direction of search and learning (Kogut & Zander, 1996).

Consensus-based hierarchies are typically comprised of cross-functional teams that smooth communication among diverse organizational functions (Hoopes & Postrel, 1999). Involvement in a cross-functional team challenges an individual's bounded rationality by exposing them to new perspectives and ways of working (Handfield, Cousins, Lawson, & Petersen, 2015; Simon, 1991). The dispersed power and decision-making apparatus of consensus-based hierarchies often makes resources more readily available to support innovative projects, giving individuals the time and financial freedom to engage in creative thinking (Felin & Zenger, 2014). In addition, consensus-based hierarchies create more frequent opportunities for individual interactions that result in experiential learning (Nickerson & Zenger, 2004). A great example here is Chrysler's design facility in Michigan, which allowed many public spaces for different platform teams to run into one another between meetings (Petersen, Handfield, & Ragatz, 2005).

Within consensus-based hierarchies, low-powered incentives can be used to encourage search, knowledge transfer and new knowledge generation (Grant, 1996b). Low-powered incentives are tied to an individual's performance and are commonly seen in large firms where individuals have a negligible effect on a firm's overall performance (Zenger & Hesterly, 1997). Low-powered incentives, such as pay awards tied to the achievement of key performance indicators, can encourage individuals to work within a collective and solve a defined problem (Zenger & Hesterly, 1997). For example, an individual may be given low-powered incentives to deliver a project on-time and in-full by working within a cross-functional project team. Low-powered incentives can thus be used to stimulate individual interactions within a collective as a means of generating new knowledge (Zenger & Hesterly, 1997). High-powered incentives, on the other hand, are tied to firm performance and are often seen in market based transactions – such as consulting contracts – or in small firms where employees can directly influence firm performance (Zenger, 1994). High-powered incentives discourage knowledge sharing and instead promote knowledge hoarding as individuals attempt to take credit for improvements in firm performance (Zenger & Hesterly, 1997). Moreover, high-powered incentives can harm consensus building because they encourage opportunism and gaming such as a CEO using share buy-backs to hit quarterly stock market targets (Zenger & Hesterly, 1997).

We note here that organizational structures, regardless of type (authority or consensus-based), act as integrating mechanisms that bring individuals together to share knowledge in some manner. Our Figure 1 suggests that consensus-based hierarchies are more likely to facilitate interaction amongst individuals and the horizontal exchange of knowledge, when compared to authority-based hierarchies. Low-powered incentives act as an important motivator to bring individuals together to share knowledge and solve problems collaboratively, while high-powered incentives lead to opportunistic behavior and discourage consensus building. Thus, Figure 1 suggests that the search for solutions to highly-complex problems, such as new technology development, is best suited to consensus-based hierarchies comprised of individuals motivated by low-powered incentives. The interaction and knowledge exchange that occurs between individuals in consensus-based hierarchies increases the likelihood of the emergence of routines and operational capabilities (see Figure 1).

2.5 | Processes interacting with structures

NPD and strategy formulation provide good examples of how processes and structures create opportunities for the individual interactions that become the microfoundations of routines and capabilities. For instance, the automotive product development process is partitioned into sequential phases including concept development, product platform design, component design, prototype building, and process engineering (Clark & Fujimoto, 1991). The individuals involved in each phase of the process are assigned according to department, such as marketing, design, procurement, operations management, and engineering. The process is further subdivided by product segment, including body, chassis, engines, transmissions, electronics, and so forth. The cross-functional nature of the automobile NPD process requires individuals from a range of departments and product segments to share knowledge (Clark & Fujimoto, 1991; Petersen et al., 2005; Primo & Amundson, 2002). In a similar manner, the strategy formulation process may include individuals from a range of departments and business units that meet to set strategic priorities and allocate resources to individuals and projects (Grant, 1996a).

Yet, while structures and processes may overlap at times, this overlap does not necessarily lead to knowledge creation or accumulation without the specific interaction of individuals who share knowledge (see Figure 1). That is, a process requires individuals to carry out a series of productive tasks (Felin et al., 2012), and organizational structures have no real purpose without the individuals to populate them. The essence of the microfoundations argument is that individuals are the essential unit of analysis for examining how organizations create capabilities. The interaction between individuals is predicted to occur at intersections where processes and structures meet. Figure 1 suggests that the design of an organization's processes and structures can explicitly encourage, or alternatively constrain, the likelihood of such individual interactions, and thus impact the likelihood of whether learning routines and knowledge creation will occur. In the remainder of the article, we apply Figure 1, related to processes, structures, individual interactions, to the additive manufacturing development program at AerospaceCo, our focal case company.

3 | METHODOLOGY

3.1 | Research design

Our research design is based on a theory building approach. We followed the guidance of Wacker (1998) who suggests that good theory-building research defines the variables, specifies the domain, builds internally consistent relationships, and makes specific predictions. In this study, we have specified the research domain (additive manufacturing development in a firm's operation), defined the key variables (individuals, structures, processes, routines, capabilities), and used the existing literature to predict the relationships between variables. Working inductively, we compared empirically gathered data to the existing literature in order to make analytical generalizations (Eisenhardt, 1989). While guided by pre-existing theoretical considerations, we remained open to unanticipated findings and the possibility that the general theory required reformulation (Merton & Merton, 1968) We reconciled the idiosyncrasies of the case with the KBV and, when unanticipated findings were identified, we built on directives suggested by knowledge-based theory.

A case study design was selected because the researchers were investigating a contemporary phenomenon about which little is known and over which the researchers had little control (Yin, 2014). We met the duality criterion of rigorous case research by ensuring the study is situationally grounded while seeking a sense of generality (Corley & Gioia, 2011; Gioia, Corley, & Hamilton, 2012). To ground the study, we looked for a company in the process of developing a digital manufacturing capability. We identified one such company in the aerospace sector, which we will call AerospaceCo that was in the process of developing a capability in additive manufacturing. The additive manufacturing development program was an ideal context to study how individuals interact with the structures and processes of the case company. We were given access to study how individuals from a range of departments overcame structural boundaries to form into cross-functional teams and rethink the new technology development process. This was a unique opportunity to examine how individuals interact with structural boundaries and operational processes at the microlevel to create operating routines and operational capabilities at the macrolevel. We selected a single case design because it provides for a more in-depth level of investigation than multiple cases (Dyer & Wilkins, 1991; Sigglekow, 2007; Voss, Tsikriktsis, & Frohlich, 2002); this allowed us to spend significant time to understand the relationship between individuals, structures, and processes at one particular firm. This allowed us to identify new empirical relationships and to elevate the theory's level of abstraction (Wacker, 1998).

3.2 | Case description

AerospaceCo is a multinational enterprise of 50,000+ employees; the firm is at the cutting edge of innovative new technology and product development for the aerospace sector. The aerospace industry has notoriously long NPD lead times (Rossetti & Choi, 2005); the focal firm is no exception, with new products being introduced to market on a 5-year rolling basis. The technologies that underpin these new products take between five and twenty years to develop and embed in a new product. The new technology development process is highly structured with technologies developed over nine stages, referred to as technology readiness levels (TRLs). Designers and engineers must satisfactorily answer a series of questions before passing through a gate and advancing to the next stage of development. The first department in the process is the Strategic Research Center (SRC), which is responsible for scanning the business horizon to identify promising new technologies that may not be ready for commercialization until 20 or 30 years in the future. The SRC typically oversees the early technology-development stages (TRL 1–4); these involve observing and reporting the basic principles of the technology, agreeing the proof of concept, and validating the technology in a laboratory environment (see Figure 2).

Supporting the SRC is the research and technology department, which is responsible for early stage new technology R&D (TRL 3–4) (see Figure 2). Once the technology passes through gate four, it then moves to the future programs department, which matches the technology to a future product, typically due to market entry in ten to fifteen years. Once allocated to a future product, the technology joins the NPD process and advances through TRL stages 5–6. The manufacturing technology department oversees TRL stages 6–9, during which time the technology is optimized for the required rate of production using production-ready equipment. Development stages 8–9 are when the technology is proven production capable in a live test environment (see Figure 2).

3.3 | Data collection

Data were collected over a 16-month period from January 2014 to April 2015. A triangulated data collection strategy was used (Yin, 2014), where we gathered primary data from semistructured interviews, meetings with the project steering committee, and participant observation. These data were objectively verified using primary and secondary company documentation. Forty semistructured interviews were conducted, with questions asked about the role of key

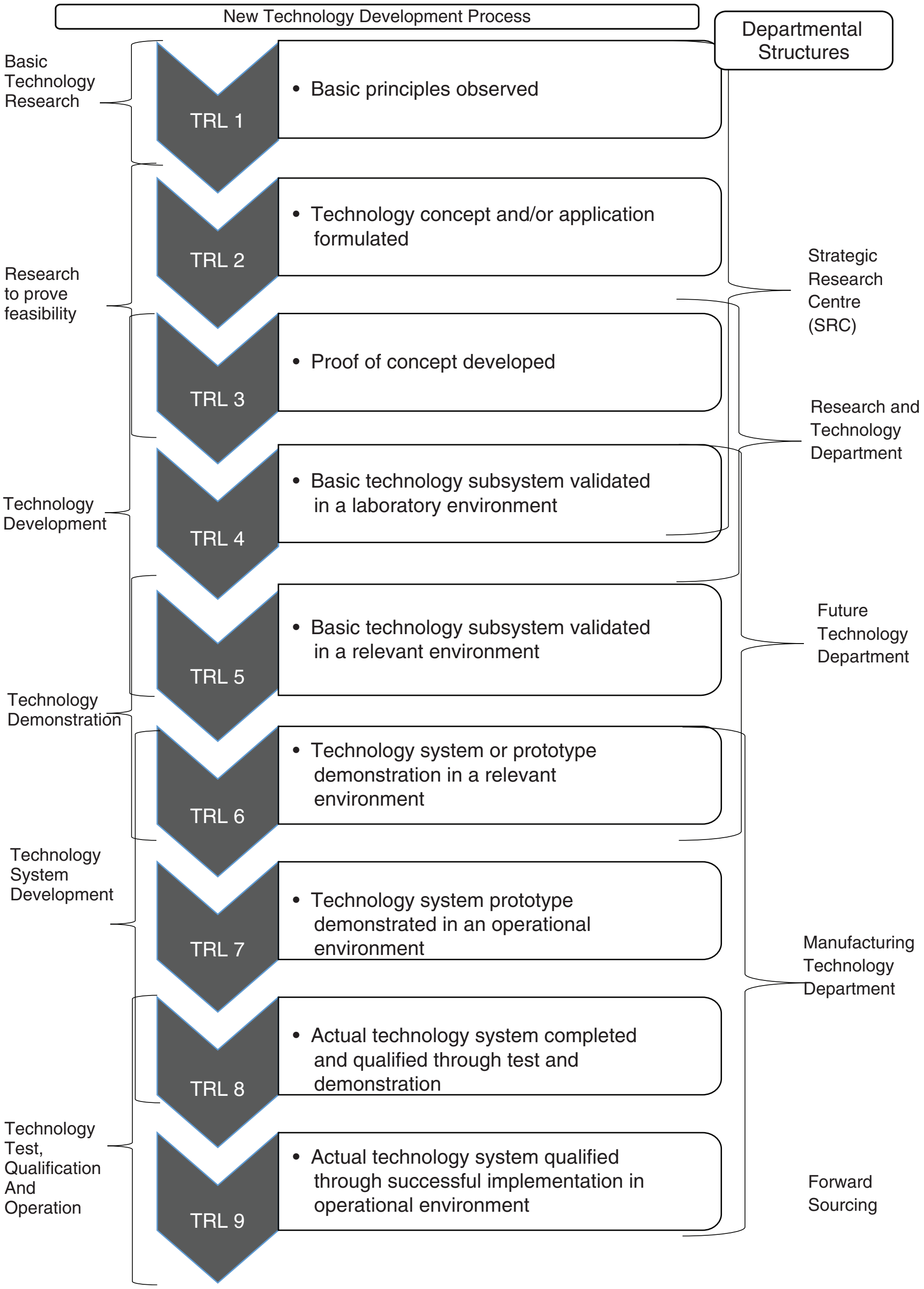

FIGURE 2 New technology development process and departmental structures [Color figure can be viewed at wileyonlinelibrary.com]

individuals, processes, and structures in the development of additive manufacturing. A semistructured format allowed standard questions to be asked; this permitted direct comparisons across job roles, departments, and organizational levels. Unstructured, probing questions allowed us to uncover unexpected information (Galletta, 2013).The interviews were conducted face-to-face and lasted between 45 minutes and an hour. The interviews were audio recorded and then transcribed verbatim. To ensure confidentiality, all names and positions were anonymized and a typed transcript was sent to interviewees for review and amendment. A total of 38 hours of interview recordings were collected, resulting in 712 pages of typed transcripts. Having conducted 40 interviews, we found that a point of theoretical saturation had been reached as no further insight, knowledge or learning was emerging from the data (Lee, 1999).

3.3.1 | Sampling

Our sampling logic was to collect data from individuals working in departments directly involved in the additive manufacturing development program. We collected data from all organizational levels including a Senior Vice President, 8 Heads of Department, 13 Team Managers, and 18 operational level employees (engineers, scientists, and technologists).

Gathering data from these different perspectives presented distinct lenses on the same phenomenon, providing deep insights on how individuals, processes, and structures interact and aggregate to operating routines and then to operational capabilities. In our sample, we included individuals from the additive manufacturing integrated project team (IPT), including the technology champion, materials specialists, and engineers. All interviewees had a minimum of 10 years' experience, with some working for the company for more than 20 years. As such, these individuals can be considered key informants, and gathering their opinions is said to be critical to the success of case study research (Yin, 2014).

3.3.2 | Project steering committee

A steering committee provided oversight for the research project. The committee was comprised of a project sponsor and nine experts in different aspects of additive manufacturing, as nominated by the project sponsor. The steering committee met every two months during the sixteen-month project (eight meetings) for a period of two hours; they directed the research team to relevant information and facilitated access to individuals and departments involved in the additive manufacturing development program. The sessions were semi-structured, giving participants the freedom to debate and challenge the interview findings and explore new areas of interest. This method provided important corroboration to the interview findings and opened up new lines of inquiry not anticipated by the researchers. During the project steering committee meetings, the interview findings were reported at the aggregate level and interviewee names were not discussed to ensure the anonymity of our sources.

3.3.3 | Participant observation

To further corroborate the interview and steering committee sessions, one member of the research team collected data using participant observation techniques (Atkinson & Hammersley, 1994; Spradley, 2016). Specifically, the researcher sat with the Forward Sourcing department for one week (September 15th to 22nd 2014) to observe their methods of working, to ask informal questions, and to gather and read company documentation. The researcher also gathered and reviewed primary and secondary documentation, which provided important objective verification of data gathered during the interviews and steering committee meetings.

3.4 | Data analysis

A coding scheme was created based on Figure 1 and used to analyze the data. We used thematic analysis techniques (Braun & Clarke, 2006) and a pattern matching logic (Yin, 2014; Webb et al., 1999) to analyze the interview and focus group transcripts, field notes, and documentation. One researcher used the coding identifiers (processes, structures, expertise, experiential learning, and pre-existing knowledge) to identify similar passages of text. Similar codes were combined and linked to higher order themes, such as microfoundations, operating routines, and operational capabilities. When passages of text did not easily fit the coding scheme, a new coding category was created and affixed to a new theme. The coding template was revised in an iterative fashion until the researchers arrived at a final template that provided a robust explanation of the case (Eisenhardt & Graebner, 2007). Identifying unexpected codes and themes played a key part in our theory building approach (Eisenhardt, 1989). Having completed an initial analysis of the data, the coding process was repeated by a second member of the research team to achieve consistency of coding and to ensure interrater reliability (Armstrong, Gosling, Weinman, & Marteau, 1997). Taking steps to address inter-rater reliability is appropriate for semi-structured interviews as all participants are asked the same structured questions in the same order, and the data are coded at the end of the data collection period (Morse, 1997). The second coding of the data resulted in close agreement on the key identified themes and enhanced the rigor of the qualitative data analysis process (Armstrong et al., 1997).

4 | FINDINGS

4.1 | Organizational changes in 2012

Prior to explaining our findings on the role of microfoundational interactions at AerospaceCo, it is important to establish the context for the organizational culture of the case company. AerospaceCo is a highly bureaucratic organization that is formed of primarily middle-aged engineers with between 10 and 30 years of on-the-job experience, working their entire careers at the company. The company follows a very well-defined new technology development process that is based on nine stages and gates described in Section 3 above (the TRL Process). New products and their supporting technologies are developed on a 10 to 20 year time horizon. Yet, despite long-lead times and bureaucratic organizational structure, the company is still considered a world leader in innovative technologies.

AerospaceCo has a very risk-averse company culture based on a tradition of incremental technology development and organic growth. This risk-averse culture stems from safety concerns and legislation imposed by aerospace regulators and has resulted in a senior leadership team that is hesitant to spend money on innovations without a solid business case and high chance of success. AerospaceCo's method of new technology development is in stark contrast to its primary competitor BigCo, who takes significant risks on new technologies without a clear business case. Over the past decade, BigCo has taken significant risks to invest in promising new additive manufacturing technologies; for example, purchasing start-up firms in the early stages of new technology development. In 2012, AerospaceCo's leadership team recognized it was not developing new technologies at the same rate as the competition; they were struggling to stay current in their portfolio of innovative technologies, including additive manufacturing.

Additive manufacturing is considered by the company to be a "whole-system technology" that can print a range of components and subassemblies for the final product. Whole-system technologies have multiple applications and do not easily fit within AerospaceCo's authority-based hierarchical structure that is comprised of departments and Supply Chain Units (SCUs); this structure is shown in Figure 3.

Figure 3 illustrates the five organizational levels within AerospaceCo: Senior Executive Team, Heads of Departments, Middle Managers (Chiefs and Team Leaders), and Operational Employees. These individuals sit within departments such as the SRC, Future Programs, Research and Technology, and Manufacturing Technology (see Figure 3). In addition, there also exist a number of SCUs, which are responsible for the development of a specific category of component (rotating parts, turbines) or subassemblies (outer casings, structures and transmissions). During additive manufacturing's early stages of development (2005–2012), it was allocated to, and owned by, the structures and transmissions SCU. The difficulty that this created was that additive manufacturing development efforts became completely concentrated within the structures and transmissions SCU, while the application of additive manufacturing to other product categories was largely ignored. Because additive manufacturing had such great potential, engineers from other SCUs independently began their own exploration into the technology, creating disjointed pockets of development. The Head of Innovation at AerospaceCo explained the predicament that additive manufacturing created for the company as follows:

> "In our company, loosely speaking, you have two groups of technologies. First, which are easier for the organization to deal with, are discrete technologies that are aligned to some of the silos we have. For example, a purely combustion technology will be owned by the combustion supply chain unit. And when it goes in to the Supply Chain Unit, it's owned by and confined within that Supply Chain Unit. Development is relatively straightforward as these technologies have pre-defined supply chains that are pretty easy to manage. The situation gets more complex where you have whole system technologies that are dependent on more than one Supply Chain Unit to deliver the hardware elements of that technology."
>
> Head of Innovation – Research and Technology

The Head of Innovation at AerospaceCo made a clear distinction in this quote between discrete and whole system technologies. Discrete technologies are things such as new materials that will be used to create one type of component or subassembly, such as the combustion system. Whole system technologies include novel manufacturing methods (i.e., additive manufacturing) that can produce a range of new components and subassemblies from rotating parts, to structures, to transmissions and combustion systems.

In 2012, the senior management team realized that whole-system technologies, such as additive manufacturing, needed a different developmental approach if the company was to remain competitive. The senior management decided to create a new initiative, called its "top 11 technology program," which sought to develop 11 key technologies toward which the company was committing strategic investments. This program assigned a technology champion and IPT (Integrated Project Team) to the additive manufacturing program. The technology champion quickly moved to set up an additive manufacturing center of competence (AMCC) with this investment. The AMCC was built as a stand-alone facility in 2014, where the IPT could experiment with and test additive manufacturing –without having to use the company's existing testing facilities. By situating additive manufacturing within the AMCC, the technology development team now sat outside the authority-based hierarchy of AerospaceCo, including the incremental new technology development process. Since 2012, additive manufacturing's development has progressed rapidly and the technology is now being used for the manufacture of multiple aspects of the final product, including rotating parts and highly critical components.

In our findings that follow, we develop the specific characteristics of the additive manufacturing initiative and how the interaction among individuals created a new operations capability within the organization that exists today. Our analysis of this transformation will cover the role of processes, structures, and the interactions that produced routines that evolved into a new operational capability in additive manufacturing.

4.2 | Individuals interacting within processes

In our data collection, we explored the extent to which formal processes acted as a coordination mechanism through which firms integrate the specialist knowledge of their members (Felin et al., 2012; Grant, 1996b). Members of the project steering committee highlighted how additive manufacturing remained in the early stages of new technology development (TRL 1–3) for seven years (2005–2012); this was due to a lack of strategic focus and a risk-averse culture at the company. Steering committee members stressed that the aerospace industry is highly regulated and safety conscious. One member

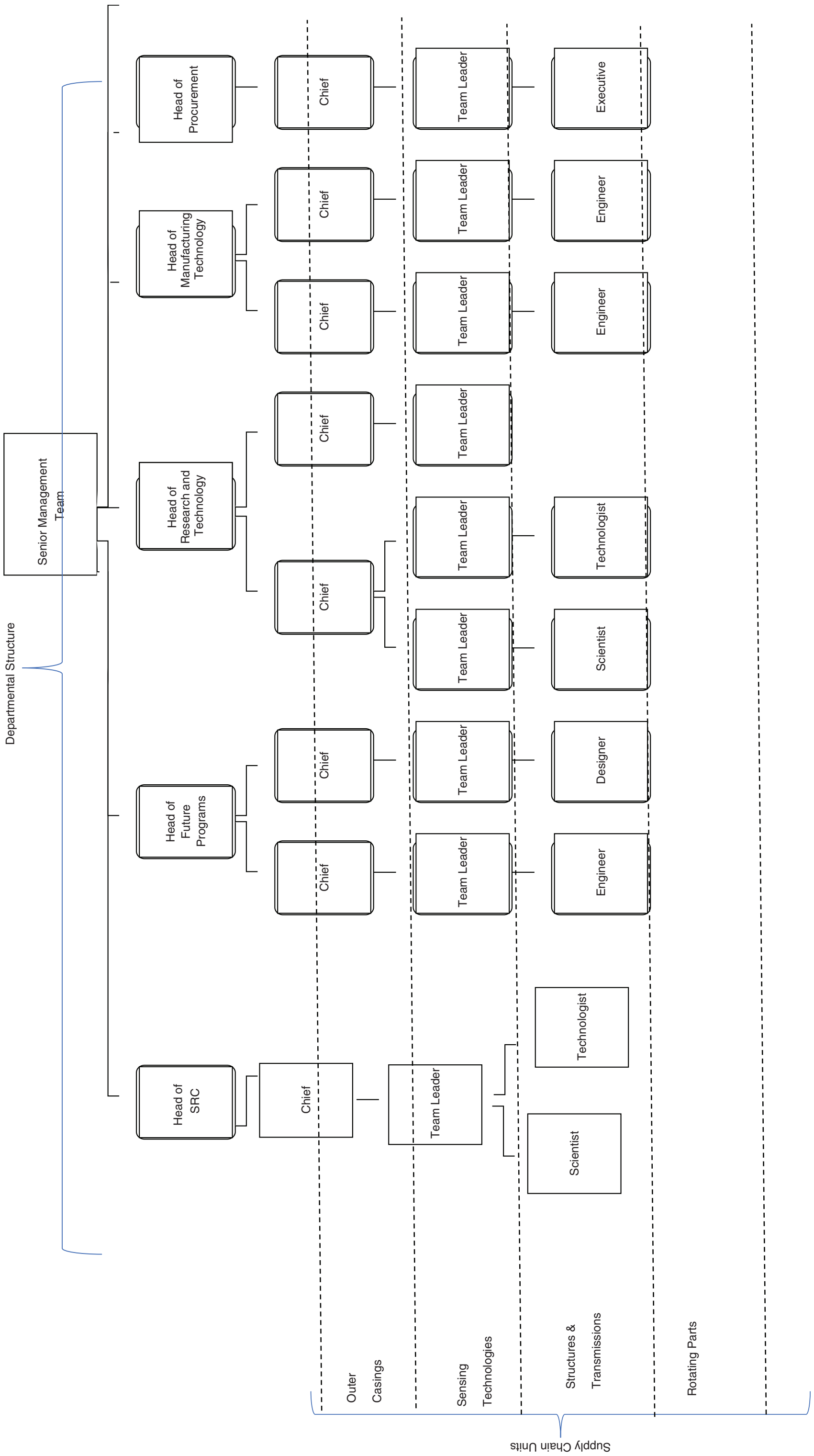

FIGURE 3 Authority-based organizational structure [Color figure can be viewed at wileyonlinelibrary.com]

believed that this created a risk-averse mind-set at the company and prevented it from taking risks on novel technologies, such as additive manufacturing:

> "I think for additive manufacturing we could have made a bigger footprint earlier on. We've talked a lot about additive manufacturing but we've not nailed our colors to the mast and said 'we are going to use this, it's not ready now, ten years from now it will be ready…Look at the pace of change, let's invest in it now'."
>
> Technologist – SRC

The steering committee went on to explain that additive manufacturing's development stalled during the early TRL stages (TRL 1–3) because of a lack of strategic focus and insufficient financial support. It was not until 2012, when the senior management team introduced the "Vision" process, that strategic focus on the key technologies to be introduced over the next 5, 10, and 20 years was set. As a part of the vision process, the senior leadership team created the "top 11" technologies program; these were 11 key technologies that would be embedded in upcoming products. The Senior Vice President of future programs described the importance of the Top 11 technology program as follows:

> "…It [technology development] is now much more market-driven…Each year, we do a strategic prioritization process, which really sets priority terms for which markets we're going to act in to make sure we're very prioritized and very focused. And that will then focus the R&T [Research and Technology] agenda. So we now have 11 key top-level strands of technology. Each of those has a team and a project-management process associated with it. So clear leadership, clear milestones, clear outputs and clear budgets."
>
> Senior Vice President – Future Programs

Upon becoming a Top 11 technology, the senior management team dedicated significant financial and human resources to additive manufacturing's development, including hiring a technology champion tasked with driving forward development. This individual described the impact of his appointment as follows:

> "We've been working in additive manufacturing for ten years. But because of varying reasons, be they business case, be they risk, be they maturity of understanding, it has taken us this amount of time to be in the position where we are in now. Development has been incremental and it's never had that shot of innovation, or intensity, that's said 'we absolutely have to do this….' Over the past twelve months, which is when I came in to this role, that concentration has happened and we've learnt so much so quickly. Focusing with firm resolve has enabled us to move our level of understanding on substantially in the past twelve months."
>
> Technology Champion

By concentrating the responsibility for the technology in a single role, this individual could bring significant experience from previous positions to the role; knowledge that he applied quickly and efficiently to realize a step-change in development – what we term "pre-existing knowledge application". The technology champion acted as a "knowledge coordinator," pulling together all the existing R&D efforts from around the company.

The technology champion established an IPT comprised of experts from the engineering, materials, supply chain, and manufacturing technology departments. The IPT acted as a focal point in the organization for all additive manufacturing activity across all SCUs:

> "So the IPTs have helped as control mechanisms. So now we've got a small number of conduits, and the IPT makes sure that everyone in the organization knows what's going on. So the IPT is a very good filter."
>
> Capability Manager – Machining and Automation

Each individual in the IPT contributed pre-existing knowledge acquired from other departments to the role. These individuals were suddenly placed together on the same team, allowing them to share knowledge through formal socialization mechanisms (team meetings, project meetings, and online digital platforms) as well as informal socialization, including lunches and team events (Cousins et al., 2006; Cousins & Menguc, 2006). For example, the members of the IPT shared ideas about additive manufacturing through information technology (IT) platforms such as the innovation portal and the big ideas forum. These platforms facilitated the free exchange of knowledge between team members and allowed individuals from around the business to send the IPT new information. We found that by interacting within the IPT, over time, individuals were able to share and add new knowledge to their existing knowledge base (as predicted by Grant, 1996b). In effect, the formal vision process brought together key individuals from across the business to share knowledge and drive forward the development of additive manufacturing, in an interactive manner that had never occurred before in the organization. These findings led us to posit the following proposition relative to new processes established within an organization:

P1: *A new process can act as an integrating mechanism that brings individuals together to share knowledge.*

Within the context of this proposition, however, there are several important caveats that also emerged during our analysis of AerospaceCo. Our first caveat is that *individuals accumulate knowledge due to the experiential learning that occurs during a process of experimentation and testing.*

4.2.1 | Learning-by-failing

Interviewees explained that novel technologies, such as additive manufacturing, are tested infrequently at the company because the chance of failure poses too great a risk to other more mature technologies. The result is that less-developed technologies, such as additive manufacturing, stall in the mid-TRL stages (TRL 5–6) because engineers are unable to prove the robustness of the manufacturing process. An individual in the future programs department summarized this view as follows:

> "For Additive Manufacturing, had we assigned that technology to the first product we thought about, we'd have had it in service probably five years now and a whole lot of experience, and our knowledge of the supply chain would be improved and everybody would want it. So we should be more willing to take a plunge as a company and push these technologies, even though they may have higher cost in the early days."
> Chief Manufacturing Engineer – Future Programs

The technology champion overcame the issues associated with the experimentation and testing processes at his company by instituting an informal process of learning-by-failing in his team. He described this process as follows:

> "We've got to be prepared to fail, we've got to be prepared to fail quicker. And in order to do that, we've got to be prepared to resource and fund the programs without a definitive direct business case benefit that is immediate."
> Technology Champion – Additive Manufacturing IPT

The technology champion stressed that learning-to-fail does not lead to defeat but allows important learning to occur, thus empowering his team to quickly move on to new opportunities. As posited by Felin et al. (2012) we discovered that the flexibility in the learning-by-failing process acted as an important integration mechanism during the development of additive manufacturing.

In contrast to the stage and gate TRL process at AerospaceCo, the technology champion encouraged a less structured approach to testing, instilling a mantra of learning-by-failing and ad hoc problem solving in the IPT. This approach allowed individuals to take risks and experiment with the technology, and, if it failed, quickly move on to the next approach. A process designed to permit failure allows people to quickly learn from their mistakes (Gavetti & Levinthal, 2000; Hoopes & Madsen, 2008). Indeed, the learning-by-failing process allowed the IPT to experiment with a range of additive manufacturing applications before settling on the direct laser deposition method.

A second caveat to Proposition 1 is that individuals *may apply new knowledge acquired from the process back to the process itself*, as part of a cycle of continuous improvement. That is, as individuals learn from their failures, they can incorporate these lessons learned and institutionalize them back to the process. In our case, the data suggest that the structured strategy formulation processes (the vision process) is what gave individuals the necessary resources to pursue the development of additive manufacturing on a larger scale. This led to a greater investment of time, money, and people (resources) that allowed the process to grow and become enhanced. As noted by Grant (Grant, 1991; Grant, 1996a), resources are the foundation for strategy formulation and act upon individuals, processes, and structures. Evidence for this second caveat became apparent when we discovered that the company would not likely have become an expert in additive manufacturing without the infusion of new learning acquired through the learning-by-failing process.

This leads us to our third caveat: *Experiential learning acquired from new process interactions leads to an increased tolerance for risk.* Risk-taking by the IPT allowed additional knowledge to be acquired about the technology's supporting supply chain, such as the sourcing of parts for equipment breakdowns and the continuous delivery of raw material powders. The technology champion emphasized that taking greater risks on novel technologies was taboo under the old process but was critical in the adoption of additive manufacturing as it opened up the ability for individuals to quickly acquire knowledge and experience through experimentation and testing. In this manner, the vision process and learning-by-failing acted as integrating mechanisms at AerospaceCo that brought individuals together to share knowledge. However, to ensure that these interactions became part of the organization's microfoundations, another element was critical: a new organizational structure.

4.3 | Individuals interacting with structures

Management scholars argue that authority-based hierarchical structures do not promote horizontal knowledge sharing amongst peers (Nickerson & Zenger, 2004). When authority is exercised in the absence of knowledge, it contaminates rather than accelerates the search for innovative solutions to complex problems (Nickerson & Zenger, 2004). We found this to be the case at AerospaceCo, a highly bureaucratic, authority-based organization that was often slow in decision-making and new technology development. One interviewee captured this sentiment as follows:

> "We tend to be a highly bureaucratic organization; it can take up to fourteen weeks to raise a purchase order for example. You can't act like that if you're trying to demonstrate new technology, and if we can be a lot more agile, we can reduce that time."
>
> Chief Engineer – Future Programs

Specifically, we found that the SCU structure constrained the development of additive manufacturing because this whole system technology can manufacture a wide range of components. One interviewee highlighted how the SCU structure created disconnect in the new technology development process at AerospaceCo as follows:

> "There appears to be a disconnect in the process, from when someone identifies a particular capability within the SCUs, because they are acting almost in silos. So if I was working in turbines and I've come across a particular technology, I'm not that keen to spread it too much around the business because I actually want it for my sector, my SCU and my commodity."
>
> Procurement Manager

This quote suggests that whole system technologies, such as additive manufacturing, do not fit neatly within an authority-based structure based on top-down decision-making. In 2012, AerospaceCo's senior management team acknowledged that, as a whole system technology, the development of additive manufacturing could no longer sit only within the structures and transmissions SCU. The vision process prompted the senior management team to look for alternative organizing structures. At this point, the technology champion argued his case for the creation of a stand-alone AMCC based on a consensus-based hierarchical structure:

> "Additive Manufacturing's development has been quite fragmented and the objective in additive is now is to create a Center of Competence that enables us to provide focus and develop additive on the key areas that we need to in a more cohesive manner."
>
> Technology Champion

The AMCC was established in 2014 and provided the IPT with a dedicated facility for the development of additive manufacturing. Having a dedicated site meant that additive manufacturing would no longer have to wait for testing slots to become available amongst a host of more mature technologies. The AMCC also increased the frequency of interactions among the IPT. The team now sat in one location and interacted and shared ideas on a daily basis. A member of the IPT explained a typical day in the AMCC as follows:

> "An average day can incorporate so many things, we can work on future technology strategy, we might work with technology developers and designers to further develop additive for our products, or we might meet with customers to discuss how we can commercialize this technology."
>
> Integrated Project Team member

This quote demonstrates how individuals from a range of departments were brought together within the AMCC to exchange knowledge on a repetitive basis and, by doing so, they gained hands-on experience with the technology. The AMCC therefore allowed the development of additive manufacturing to break free of the bureaucratic SCU structure that had constrained it in the past. One member of the IPT further clarified how this new structure prompted repetitive interactions between individuals:

> "What the Center does is it allows us to bring the designer and the manufacturing engineer together to further prove the process and industrialize the technology so that we can realize production to aviation standards."
>
> Integrated Project Team member

This quote highlights how the new AMCC structure brought individuals together to demonstrate the technology and prove the robustness of the process; allowing the technology to advance through the mid- to late-TRL levels (TRL 5–9). Members of the IPT argued that the AMCC marked a step-change in development precisely because it was a consensus-based hierarchy. By being unencumbered by the authority-based structure of AerospaceCo, the activities of the IPT were no longer constrained by the company's bureaucratic processes or risk-averse culture. Knowledge sharing within the consensus-based hierarchy of the AMCC was encouraged by low-powered incentives tied to advancing additive manufacturing through the TRL process and achieving project-level and strategic-level milestones, as explained by the Technology Champion:

> "So there are TRL milestones, there are high-level Research and Technology milestones. As [Additive Manufacturing] is a top 11 technology, I have a major board-level milestone, which the team is going to hit.
> Technology Champion

Low-powered incentives were tied to the ability of individuals within the IPT to mature additive manufacturing through the TRL stage-and-gate process, with the overall completion of project milestones monitored at board level. Such low-powered incentives encouraged knowledge generation as the members of the IPT shared ideas to address the problem of how to fully develop additive manufacturing to the point where it was production ready. Here, we find support for our second proposition (P2) that knowledge is shared among individuals at the point where processes (new technology development) interact with structures (consensus-based hierarchies):

P2: *Individuals share knowledge when they interact at the intersection of structures and processes.*

Organizational structures and processes can constrain the creativity of individuals, resulting in potential capabilities not being realized. Some authors argue that it is often serendipity that results in capabilities coming to the fore (Denrell et al., 2003). While this may be the case in some situations, we found that it was an individual collective that formed a consensus-based structure, which in turn overrode the authority-based bureaucracy of AerospaceCo. In a sense, the consensus-based structure and learning-by-failing process evolved (Hodgson, 2012; Winter, 2013) to find a way to build the capability from the micro to the macro level. Therefore, while the microfoundations literature recognize the importance of the individual, it is the ways in which individuals (and collectives) interact, including their various behavioral aspects (e.g., culture, leadership style, etc.), with the structures and processes of the firm that ultimately enabled the formation and development of operational capabilities in this case.

Proposition 2 provides insights into where knowledge exchange between individuals is likely to occur. The third proposition to emerge from our research concerns how the interaction between individuals at the intersection of structures and processes leads to the emergence of operating routines: this is described next.

4.4 | The microfoundations of operating routines and operational capabilities

Our findings suggest that while rigid processes such as the TRL process helped to integrate individuals into crossfunctional teams, these processes did not necessarily promote interaction. It was not until the consensus-based structure of the AMCC was established that the individuals were able to dedicate their time to carrying out processes such as experimentation and testing. Moreover, having low-powered incentives tied to maturing additive manufacturing through the TRL process brought individuals together to solve well-defined problems and create knowledge. Within the AMCC, the technology champion's mantra of learning-to-fail was closely adhered to by the IPT members; over time, an operating routine emerged where members would fail and quickly move to the next iteration of technology. Here, we see how the interaction between the learning-to-fail process and the AMCC consensus-based structure created a space where individuals could repetitively interact, and through this interaction operating routines emerged. In a sense, individuals gained a new power through the interaction of technological change and a new social structure emerged driven by the consensus-based structure and reorganized process (Holweg & Pil, 2008).

In addition, the findings highlighted that because BigCo had pulled ahead in the race to develop additive manufacturing, AerospaceCo was under competitive pressure to quickly move development efforts forward. To do so, IPT members often reverted to flexible ad hoc problem solving processes to fix issues on the job as they arose. Often, this problem solving occurred outside of the TRL process. Over time, these ad hoc problem solving processes became embedded in the team's way of working and were routinized within additive manufacturing's development program. Importantly, the AMCC gave the IPT the freedom to work in such a manner, outside of the rigid TRL process. The process and structural interaction that occurred with the AMCC allowed individuals to operate within a set of guidelines that provided some flexibility and creativity to the outputs of the interactions that took place.

These findings lend support to Zollo and Winter's (2002) claim that experience accumulation and deliberate learning lead to the emergence of operating routines. Operating routines are static and allow for knowledge to be easily transferred between individuals without significant knowledge loss (Grant, 1996b; Peng et al., 2008; Zollo & Winter, 2002). Figure 4 advances an empirical framework of the interaction between individuals that occurs at the nexus of structures and routines.

Once processes such as learning-by-failing and ad hoc problem solving became routinized within the AMCC, the development of additive manufacturing advanced quickly, moving through the mid to late development stages (TRL 5–9). This leads us to our third proposition:

P3: *Interactions between individuals at the intersection of structures and processes will lead to the emergence of operating routines.*

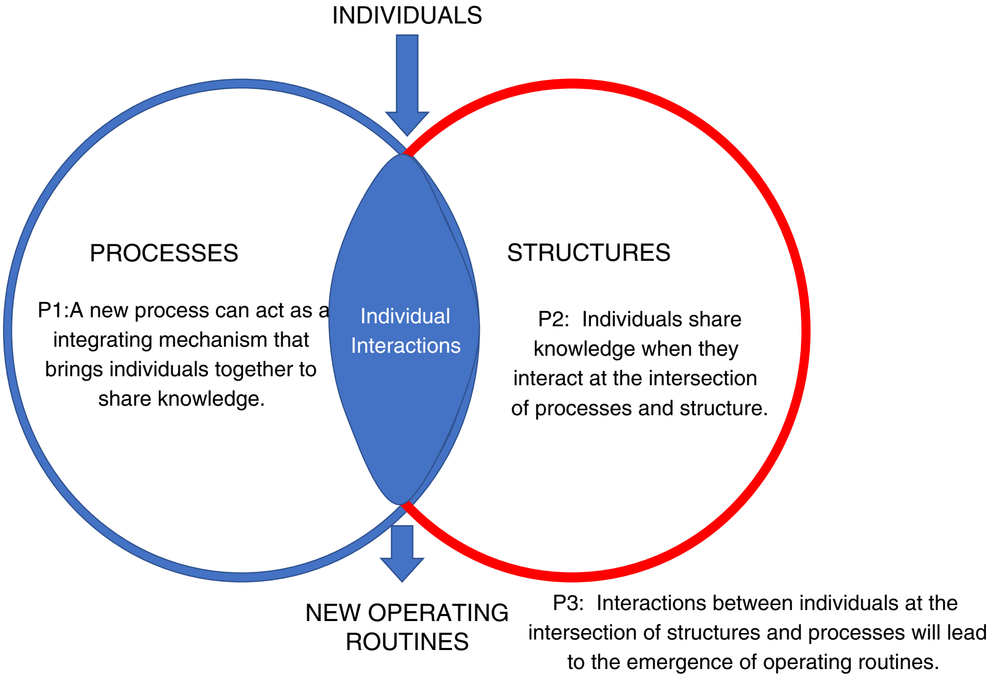

FIGURE 4 Emerging propositions [Color figure can be viewed at wileyonlinelibrary.com]

Proposition 3 is kept deliberately broad, in that it suggests operating routines are likely to emerge from the interaction between individuals, processes, and structures regardless of the new technology being developed. We go on to suggest that the type of technology being developed, be it a discrete or whole system technology, will influence the configuration of processes (flexible/rigid) and structures (authority and consensus based) that bring individuals together to interact and share knowledge.

We have seen how whole system technologies do not fit neatly within the existing authority-based structure of AerospaceCo. Our findings suggest that novel whole-system technologies, such as additive manufacturing, require flexible processes (ad hoc problem solving and learning-by-failing) as well as consensus-based structures, such as the AMCC. Examples of other such whole system technologies currently being adopted by organizations include the Internet of Things (distributed computing), Artificial Intelligence for the coordination of supply chains, and machine sensing technologies. Importantly, we stress that when establishing new consensus-based structures for emerging technologies, companies should ensure centers of competence sit outside the authority-based structure of the firm. We propose the following:

P4: *The development of whole-system technologies is better suited to consensus-based structures and flexible processes as they increase the frequency of interactions between individuals from across the firm.*

Collectively, these propositions support the idea that interactions between individuals, processes, and structures leads to the emergence of operating routines. Consensus-based structures that are unencumbered by authority-based hierarchies permit the emergence of new ad hoc problem solving and learning-by-failing processes, which over time become routinized as flexible operating routines. When combined and put into practice, these operating routines allowed the case company to build an operational capability in additive manufacturing. This finding lends support to Peng et al. (2008) who argued that it is the synergistic interplay between operating routines that leads to the development of an operational capability.

Several examples from the case suggest how powerful this operational capability has proven to be. AerospaceCo has started to realize significant performance improvements from its investment in additive manufacturing capabilities. Specifically, additive manufacturing has given designers the capability to print novel forms, allowing them to design components based on functionality instead of the traditional limitations of casting and forging manufacturing methods (2018 AerospaceCo annual report). Additive manufacturing is improving production lead times at the company, as many components are no longer sourced from overseas suppliers, but are made onsite. In addition, additive manufacturing is improving the quality and cost of the final product by reducing raw material inputs and cutting redundant steps in the manufacturing process (additive manufacturing strategy document). The technology is expected to generate 85% less raw material waste and reduce lead times through one-piece manufacturing; also, parts will be lighter, which offers substantial fuel consumption savings (2018 AerospaceCo annual report).

5 | DISCUSSION AND CONTRIBUTION

5.1 | Theoretical contribution

OM scholars have explained how operating routines can be bundled together and deployed as operational capabilities (Adler et al., 1999; Peng et al., 2008; Swink et al., 2007). However, there has been little exploration at the microfoundational level to explain what factors lead to the emergence of operating routines and operational capabilities. Our paper contributes to knowledge-based theory by answering the call of strategy scholars to open up the black box that comprises the microfoundations of routines and capabilities (Abell, Felin, & Foss, 2008; Barney & Felin, 2013; Felin et al., 2012). We have offered an empirically informed framework (see Figure 4) that establishes the basis for exploration of process and structural interactions in the emergence of new operating routines and operational capabilities. The literature (c.f. Barney & Felin, 2013) on microfoundations suggests that capabilities can remain dormant if individuals are constrained by structures and processes (including behavioral aspects such as culture). However, we found that individual collectives, when highly motivated, were able to "evolve" beyond authority-based structures and increase their opportunities for knowledge exchange interactions. We found that individuals within the IPT were motivated by low-powered incentives that encouraged problem solving and knowledge co-creation to advance additive manufacturing through the stage-and-gate TRL process. The increased interactions that occurred within the consensus-based AMCC structure, combined with the flexible learning-by-failing process, allowed knowledge to aggregate from the microfoundational level to form macrolevel routines and capabilities.

Our theoretical contribution is novel because it is the first to present a granular depiction of how different types of technologies (discrete/whole-system) require different combinations of rigid/flexible processes and authority-based/consensus-based hierarchical structures to encourage individuals to interact and share knowledge. These findings provide a counterpoint to the traditional OM literature that characterizes NPD as a 'process' that requires well-connected buyers and suppliers, and cross-functional teams to drive down costs and enhance final product performance (Petersen et al., 2005; Ragatz, Handfield, & Scannell, 1997). These studies assume that processes, in isolation, bring individuals together, but ignore the fact that structures can act as a countervailing force that keeps individuals apart. A case in point is how the authority-based structure of AerospaceCo actually inhibited the development of Additive Manufacturing. Financial and human resources were focused on the Structures and Transmissions SCU, and individuals from other SCUs felt ignored and started their own R&D efforts, leading to disjointed development efforts across the business.

5.2 | Managerial contribution

Our framework (see Figure 4) provides managers with a roadmap on how to implement the appropriate structures and processes when pursuing an operational capability in digital manufacturing. Our results suggest that an authority-based hierarchical structure is wellsuited to the development of discrete technologies that will be used in one area of the final product. However, to exploit the capability of additive technology to manufacture a range of components across different product platforms, managers should establish a consensus-based hierarchical structure that sits outside of the authority-based structures of the firm. Sufficient resources will need to be dedicated to such development efforts (financial, time, equipment, and human resources) including a technology champion to coordinate development efforts and an IPT with a broad range of knowledge and experience. Establishing a Center of Competence offers Operations Managers the potential to dramatically reduce development lead times by allowing teams to operate unencumbered by authority-based constraints and risk-averse company cultures. Low-powered incentives can be used to encourage interactions amongst individuals, stimulating the cocreation of knowledge during the problem-solving process.

Our research also supports the idea that additive manufacturing is not simply a "flash in the pan," but when combined with the powerful digital technologies emerging today, can become a powerful competitive advantage. In our case, additive manufacturing allowed AerospaceCo to cut waste in the production process by 85%. At the same time, additive manufacturing dramatically reduced production lead times from one product every 2–3 weeks in the past, to 7 final products per week today (AerospaceCo company website, 2018). These findings illustrate that matching the type of technology, be it discrete or whole-system, to the appropriate type of processes and structures allows Operations Managers to compete on multiple performance objectives simultaneously. The findings also support the idea that technology must be combined with the appropriate organizational structures that allow people the freedom to experiment and learn how to exploit such technologies.

5.3 | Limitations and future research directions

This study used a case design and a theory building approach to explore the microfoundational interactions that lead to the emergence of operating routines and operational capabilities. Because a single case design was used, we do not claim that the findings are generalizable to wider populations (statistical generalization). Future studies are needed to generalize and validate the propositions within our framework (Figure 4), by collecting data from a wider sample of firms, either using a multiple case design or survey method. Such studies could lead to further refinement of our propositions to identify whether different types of underpinning technologies require different configurations of structures and processes, and whether these configurations change by industry and/or country.

Further, this article was limited to an examination of the role of microfoundations in the emergence of operating routines and operational capabilities. Further research is needed to determine the microfoundations of search routines and dynamic capabilities (Peng et al., 2008; Zollo & Winter, 2002). Search routines seek to bring about desirable changes in an existing set of operating routines for the purpose of enhancing profit in the future (ibid). As search routines modify operating routines, they often facilitate dramatic shifts in an operation and are therefore said to support dynamic capabilities (Zollo & Winter, 2002). Because search routines modify operating routines (Zollo & Winter, 2002), we expect that the microfoundations of search routines will stem from individuals interacting with flexible processes and non-bureaucratic organizational structures. This is an important component of operations strategy, namely the identification of how flexible processes and structures integrate the knowledge of individuals to allow an operation to compete in dynamic environments. We believe this is fertile ground for future research on the important topic of microfoundations.

6 | CONCLUSIONS

Our findings support the assertion of OM scholars (Ferdows & De Meyer, 1990; Flynn et al., 1999; Flynn & Flynn, 2004) that operational capabilities are not mere trade-offs between performance objectives (costs/flexibility and speed/dependability). Instead, we suggest that consensus-based hierarchical structures, such as Centers of Competence, create a new operational capability—the flexibility to learn by trial-and-error and a platform for knowledge exchange that can drive down costs. The research suggests that companies developing “discrete technologies” (which focus on a single component or sub-assembly of a final product) can use rigid processes and authority-based structures to deploy them. However, such rigid processes can actually constrain the development of whole system technologies by not allowing individuals to interact and learn through failure. We suggest that whole-system technologies require new consensus-based structures (i.e., Centers of Competence) and flexible processes (i.e., ad hoc problem solving and learning-by-failing) to increase the frequency of interactions between individuals. These findings can be applied to a broader range of industrial settings and organizations and provide a new foundation for research exploration on the role of microfoundational interactions in operations management.

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