Vertical integration and performance in modern manufacturing firms:

the role of knowledge and product complexity

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Abstract

Purpose – We explore how the vertical integration of pre- and post-production activities affect performance through their contribution to firm's core production capabilities. Viewing manufacturing firms as a nexus of interdependent activities, we articulate the effect of vertical integration on the effectiveness and transaction cost associated with knowledge transfer. The role of product complexity and the complexity of knowledge involved are also considered in relation to vertical integration.

Design/methodology/approach – We develop a Python algorithm to text-mine from Annual Reports of 7,740 manufacturing firms in the United Kingdom over the 2003–2019 period. This allows us to construct a longitudinal data set capturing firms' non-production activities, covering pre-production (e.g. R&D, design) and post-production (e.g. distribution, logistics). Using fixed-effects and system generalised method of moments (GMM) estimators, we investigate how the integration of different functions impact firm performance, and the moderating role of product complexity.

Findings – The vertical integration of pre-production activities – but not the integration of post-production activities – is performance-enhancing. The integration of both pre- and post-production activities is also performance-enhancing. Product complexity exhibits a U-shaped moderating effect on the relationship for pre-production and post-production activities individually, but not for both types of activities together.

Originality/value – This study contributes to the Knowledge Based View (KBV) and Transaction Cost Economics (TCE) debate, focusing on the role of knowledge exchange hazards. We shed light on the connection between product complexity and the complexity of knowledge involved in manufacturing firms and contribute to the supply chain management literature via an activity-based conceptualisation of vertical integration.

1. Introduction

In today's market environment, direct production activities – converting raw materials and components into finished products – are no longer enough for manufacturing firms to generate competitive advantage. Instead, manufacturing firms increasingly incorporate a range of interrelated activities, from R&D to design, distribution and after-sales service, to support core production processes (Hauge and O'Sullivan, 2020). Therefore, today's manufacturing firm often acts as a nexus of interdependent functions seeking to cultivate their effective synergy (Turkulainen and Ketokivi, 2012; Swink and Schoenherr, 2015). Furthermore, the effective transfer and deployment of knowledge is now critical to competitiveness as many production processes become increasingly sophisticated and knowledge-intensive (Tan and Wong, 2015).

In understanding these shifts, the transaction cost economics (TCE) and the knowledge-based view (KBV) offer valuable insights into whether firms should perform certain functions in-house. The TCE espouses avoiding transaction costs as the key driver of vertical integration decisions, while the KBV emphasises gains from more efficient knowledge transfers. Although the TCE and KBV perspectives appear divergent, they converge on the premise that firms seek to minimise transaction costs related to knowledge transfer, that is knowledge exchange hazards (KEH) (Heiman and Nickerson, 2002).

Tacit knowledge, which often resides within human language or schema, presents considerable transfer challenges (Polanyi, 2009), requiring frequent use of high-communication channels (HCC) and idiosyncratic communication codes (ICC). However, greater use of these mechanisms increases firms' exposure to KEH (Heiman and Nickerson, 2002). We argue that vertical integration amplifies the effects of HCC and ICC – more efficient knowledge transfers, as well as greater KEH exposure – which affect performance positively and negatively, respectively. The relative size of these two opposing forces determines whether the net impact of vertical integration on performance is positive or negative.

Empirical studies of vertical integration and performance show mixed results, indicating that such a relationship is nuanced and context-dependent. Forbes and Lederman (2010) discovered that in the US airline industry, vertically integrated companies tend to outperform their non-integrated counterparts. Contrastingly, Li *et al.* (2017) observed a negative impact of vertical integration on the performance of Chinese manufacturing firms, suggesting that integration might create opportunities for rent-seeking behaviours. At the same time some scholars argue that outsourcing certain non-core activities improves productivity by allowing firms to concentrate on their core capabilities (Quinn and Hilmer, 1994), while others highlight the risk of disrupting crucial links between R&D and manufacturing (Pisano and Shih, 2009).

A major limitation of the extant literature is the focus on manufacturing firms' core production capabilities, without much consideration of the corresponding ancillary activities. Moreover, as manufacturing becomes ever more sophisticated, the quantity and quality of knowledge input required also rise, posing challenges for knowledge transfer. The ability to manufacture high-value-added complex products is considered a hallmark of economic development, since it necessitates the effective management and application of a large body of specialist knowledge (Felipe *et al.*, 2012). Hence, product complexity holds another important puzzle in the relationship between vertical integration and performance (Inman and Blumenfield, 2014), especially given the apparent link between product complexity and knowledge complexity (Zhang and Thompson, 2018). Yet, despite this connection, there is scant research on the role of product complexity, negating a major contingent variable (Blome *et al.*, 2014; Eckstein *et al.*, 2015; Dubey *et al.*, 2020).

Existing studies rely predominantly on cross-sectional data, which limits the inference towards causation (Atalay *et al.*, 2014). Crude measures of vertical integration, such as the Adelman index (Adelman, 1955) or input–output metrics (Davies and Morris, 1995), are often employed, which do not accurately capture the varied impacts across different stages of the value chain (Brandt *et al.*, 2022; Peyrefitte and Golden, 2004). Additionally, the focus on specific manufacturing sub-sectors, such as cement (Hortaçsu and Syverson, 2007), machine tools (Pieri and Zaninotto, 2013) and food processing (Natividad, 2014), limit the generalisability to the broader manufacturing sector.

We address some of these shortcomings by compiling a longitudinal data set obtained from processing large volumes of company annual reports to extract keywords relating to various economic activities (Kharlamov and Parry, 2021). This covers a total of 7,740 manufacturing firms in the UK over the 2003–19 period. Regression results indicate that the vertical integration of pre-production activities – but not the integration of post-production activities – is performance-enhancing. The integration of *both* pre- and post-production activities is also performance-enhancing. These relationships are moderated by product complexity.

Our study makes three main theoretical contributions. First, we contribute to the KBV and TCE debate, emphasising the role of KEH as the primary driver of vertical integration choices and firm performance. Second, we examine the effect of product complexity, contributing to an understanding of the connection between knowledge complexity and product complexity in the manufacturing context. Third, we contribute to the supply chain management literature via an activity-based conceptualisation of vertical integration that considers the complexity of supply chains together with product complexity. Our findings also have some implications for managerial practice.

2. Conceptual background

2.1. The determinants of vertical integration choices

Transaction cost economics (TCE) is a key theory used to explain firms' vertical integration choices (Williamson, 1985). High transaction costs encourage integration to mitigate opportunism, while low transaction costs encourage vertical disintegration through greater specialisation (Jacobides, 2008). The knowledge-based view (KBV) offers an alternative paradigm to explain firm boundary choices – firms integrate certain economic activities primarily to promote the sharing of critical knowledge (Foss, 1996). Vertical integration fosters internal knowledge generation (Nickerson and Zenger, 2004) and application (Grant, 1996) by establishing a common identity, code of interaction and set of organising principles to enable more efficient transfers of knowledge inside the organisation rather than via the market (Foss, 1996; Kogut and Zander, 1992).

The presence of tacit knowledge, however, raises the verification cost considerably due to such knowledge being predominantly embedded in humans in informal and linguistics forms (Polanyi, 2009). To alleviate this problem, firms have frequent in-person meetings, close personal interactions and in-depth discussions to more accurately and effectively communicate ideas. These practices, which Heiman and Nickerson (2002) refer to as high-bandwidth communication channels (HCC), deliver rich contextual information, provide the transparency and clarity to mitigate hurdles associated with the transfer of tacit knowledge. Firms may also adopt a common cultural or linguistic framework, or idiosyncratic communication codes (ICC), to enhance communication between groups with different specialist knowledge. The use of HCC and ICC, however, exposes the firm to knowledge exchange hazards (KEH) (Nickerson and Zenger, 2004). KEHs include unintended knowledge transfers (knowledge appropriation hazard) and partisan manipulation of the knowledge accumulation process (strategic knowledge accumulation). These hazards are comparable to the opportunism that arises during contracting (Oxley, 1997).

Vertical integration amplifies the effects of HCC and ICC (Grant, 1996; Kogut and Zander, 1996) by creating the conditions for close interaction as internal units (Grant, 1996; Zander and Kogut, 1995). It incentivises internal exchanges over external ones (Natividad, 2014), similar to equity-based strategic alliances (Gudergan *et al.*, 2012). Integrated functions have incentives to adopt the same language and code in anticipation of long-term collaboration (Kogut and Zander, 1992; Zander and Kogut, 1995). However, the internal flow of tacit knowledge becomes much more difficult to regulate (Szulanski, 1996), potentially increasing KEH exposure (Oxley, 1997).

2.2. Economic activities in modern manufacturing firms

Modern manufacturing firms often derive significant value propositions via key non-production activities that support core production capabilities. Current categorisation of manufacturing firms based on industry/sector (e.g. by SIC/NACE) inadequately captures firms' idiosyncratic sets of activities that exists within the same manufacturing division. As a case in point Table 1 shows three firms that are all designated as motor vehicle manufacturers, yet engage in differing sets of ancillary activities.

Table 1. Examples of three car manufacturers engaging in different ancillary activities

Section C: Manufacturing		
Division 29: Motor vehicles		
Firm A	**Firm B**	**Firm C**
Production (of vehicles) only	Production (of vehicles) (In-house) R&D Distribution	Production (of vehicles) Wholesale Retail

In order to capture these intra-industry variations, we separate the range of supporting activities into *pre-production* and *post-production* activities. *Pre-production* encompasses activities such as R&D, design and engineering, which involve preparatory work *before* production begins. These activities often deal with products and processes still in the conceptual or planning stages. As a result, they address problems that are relatively ill structured (Håkanson, 2010). During the pre-production phase, insights from past experiences play a crucial role in driving creativity and innovation (Nonaka and Takeuchi, 2007). Hands-on experience embodied in experts helps them to make informed judgements, recognising patterns and deriving intuitive solutions in the face of fundamental uncertainties (Polanyi, 2009). This is critical to the experimentation of ideas among the vast space of possible solutions, greatly reducing the search costs (Nickerson and Zenger, 2004). Therefore, tacit knowledge likely plays a key role in pre-production activities.

Post-production covers many logistical functions, such as distribution and warehousing, that manage the physical transfer of products to customers *after* production. These activities are important in relaying customer feedback to enhance the quality of goods and achieve customer satisfaction (Swink *et al.*, 2007; Yu *et al.*, 2013). They are an important channel to reach customers, enabling the servitisation business models that are common in certain manufacturing divisions, such as machinery and equipment (Baines *et al.*, 2009). Unlike pre-production, post-production activities handle physical goods that have completed production, which have little room for substantial changes. Post-production activities address problems that are relatively well structured. Examples include determining optimal storage locations and ensuring timely delivery, which have more clearly defined goals, constraints and solutions. These problems require greater input of codified explicit knowledge with less ambiguity (Nonaka, 1994), such as common protocols governing set procedures in storage and delivery (Christopher, 2016).

2.3. Conceptualisation of vertical integration

Various forms of integration are widely discussed in academic literature, including supplier, customer and internal integration (Flynn *et al.*, 2010). These are encompassed by the notion of cross-functional integration (Swink *et al.*, 2007; Swink and Schoenherr, 2015). Typically, vertical integration refers to firms' "make-or-buy" decision, choosing whether to outsource or produce an input in-house (Williamson, 1985). This conventional view is based on a value-chain perspective of manufacturing firms with clearly defined production stages (Porter, 1985; Santos and Eisenhardt, 2005), in which integration with suppliers of raw materials or parts is considered "upstream", while integration with subsequent stages is viewed as "downstream".

As mentioned, modern-day manufacturing firms often do not engage solely in direct production activities. Moreover, value chains have evolved increasingly complex linkages (Manuj and Sahin, 2011; Vachon and Klassen, 2002). Hence, rather than seeing a firm as responsible for a particular stage of production, it should be treated as a nexus of interdependent activities (Turkulainen and Ketokivi, 2012; Swink and Schoenherr, 2015). We adopt this holistic view of manufacturing firms, dividing activities that support firms' core production capabilities into pre- and post-production following Butollo and Schneidemesser (2022). This conceptualisation and how it differs from the conventional value-chain-based understanding of vertical integration is illustrated in Figure 1. Instead of focusing on the stage of production within the value chain, our primary focus is the spectrum of *activities* and the nature of the problem.

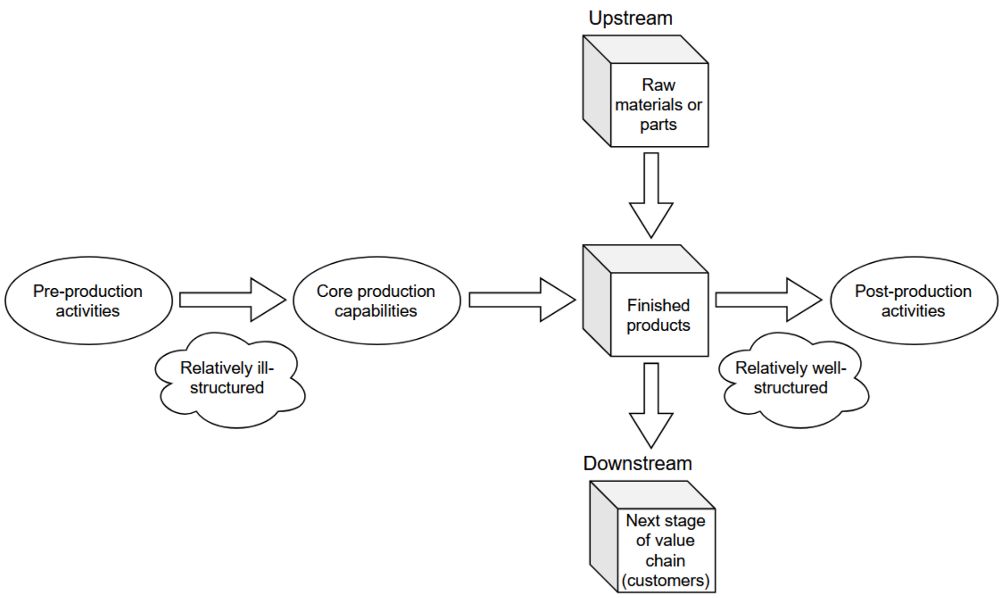

Figure 1. Comparison of conventional value-chain conceptualisation of vertical integration (vertical) and our conceptualisation based on activities (horizontal)

2.4. Role of product complexity

Complexity can be understood from a number of dimensions, such as at the industry or supply chain level. We examine complexity at the product level, the most relevant scope given our focus on manufacturing firms. Product complexity is often represented by the number of distinct components and interactions between them at the architectural level (Ulrich, 1995). Complex products consist of more components and exhibit intricate interdependencies between components and modules, which restricts their decomposability into sub-problems (Baldwin and Clark, 2000). Existing studies often treat product complexity as a contingent environmental variable that influences production costs, but they do not explain how it affects vertical integration and organisational choices (Blome *et al.*, 2014; Eckstein *et al.*, 2015; Dubey *et al.*, 2020). The manufacture of complex products poses significant challenges for coordination at both the firm and supply chain levels, imposing extra administrative costs (Trattner *et al.*, 2019). Firms often resort to solutions such as modularisation (Baldwin and Clark, 2000; Voordijk *et al.*, 2006) and project-based organisations in order to mitigate the managerial cost, especially for high-cost, complex products and systems (Hobday, 1998; Hobday *et al.*, 2000).

Zhang and Thompson (2018) argue that technical knowledge complexity, knowledge diversity and the number of knowledge interfaces all increase considerably as product complexity rises. The number of possible interactions between these dimensions can increase exponentially as a result (Kleinsmann *et al.*, 2010). The large number of possible ways that components, modules and interfaces can be combined implies that tacit knowledge is needed to enable more efficient solution searches, magnifying the returns to vertical integration (Grant, 1996; Levinthal, 1997; Nickerson and Zenger, 2004).

3. Theoretical framework

Vertical integration amplifies the effects of HCC and ICC. The KBV and TCE suggest that integrating an economic function enhances efficient transfers of tacit knowledge, but it also contributes to greater exposure to KEH, which reduces performance. These two opposing channels are shown in Figure 2, denoted by circle-enclosed 1 and 2, respectively. The net effect on performance depends on the relative magnitude of these two forces.

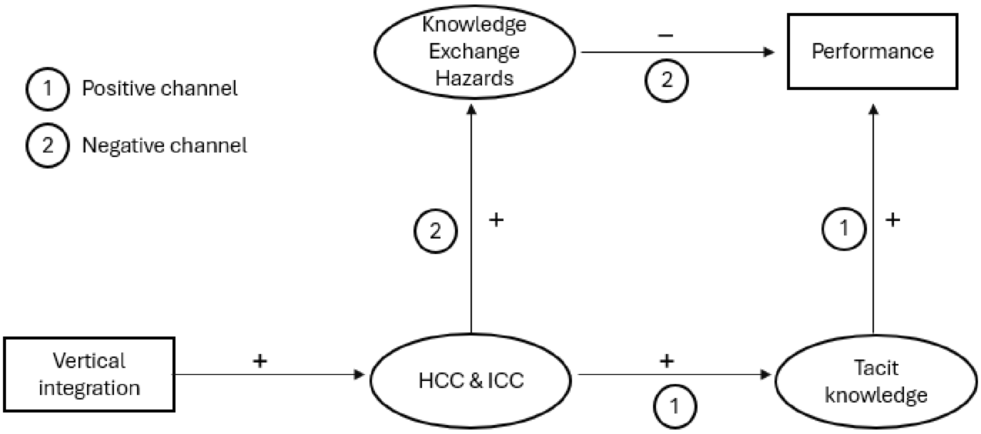

Figure 2. Vertical integration's impact on firm performance, the positive and negative channels

Pre-production activities such as R&D, design and engineering, concern relatively ill structured problems, which require greater transfers of tacit knowledge to and from the production stage for two reasons. First, among the number of productively viable designs, tacit knowledge contributes to an overarching knowledge structure and criteria to shortlist those that are most consistent with the firm's chosen strategy and business model, be that cost leadership or market differentiation (Nonaka and Takeuchi, 2007). Second, during production, tacit knowledge facilitates information feedback to the design stage to be correctly understood, regarding actual quality, costs and other attributes and how they can be improved through modification of designs (Eisenhardt and Tabrizi, 1995; Thomke, 2003).

Greater reliance on tacit knowledge means the positive channel of vertical integration is likely to outweigh the negative channel in the case of pre-production activities. Based on this, we state our first hypothesis:

> ***H1.*** *The vertical integration of pre-production activities is positively associated with firm performance.*

Post-production activities such as logistics, distribution and warehousing, and physical delivery of products, concern relatively well-structured problems, which require fewer transfers of tacit knowledge to and from the production stage for two reasons. First, being relatively standardised, the requirements of the post-production function can be more easily communicated to the production team, such as what quantities and specifications to produce. Second, the tacit knowledge gained through post-production's direct relationship with customers, such as greater awareness of market preferences and tastes, is less valuable to the production team since the scope for substantial product modifications to incorporate this knowledge would be limited without access to product design (Hayes and Pisano, 1994; Fawcett *et al.*, 2007).

Less reliance on tacit knowledge means the positive channel of vertical integration is likely to be outweighed by the negative channel in the case of post-production activities. Based on this, we state our second hypothesis:

> ***H2.*** *The vertical integration of post-production activities is negatively associated with firm performance.*

When firms integrate *both* pre- and post-production activities, there is greater need to transfer tacit knowledge between all three stages of production: between the design and production stages, tacit knowledge is needed to select and implement the most appropriate product designs; and between the production and post-production stages, tacit knowledge of customer insights needs to be incorporated into production, which is more valuable as there is greater room for product modification working with an internal design team. This contributes to innovative designs that are not only cost-effective but also more likely to match customer preferences.

Greater reliance on tacit knowledge means the positive channel of vertical integration is likely to outweigh the negative channel when firms integrate both pre- and post-production activities. Based on this, we state our third hypothesis:

> ***H3.*** *The vertical integration of both pre- and post-production activities is positively associated with firm performance.*

Regarding the integration of pre-production activities, for less complex products, there are fewer knowledge interfaces and potential interactions between the pre-production and production stage, implying a relatively well-structured problem space, which reduces the relative need to transfer tacit knowledge. At the same time, specialist knowledge associated with pre-production activities are at risk of appropriation, hence the negative impact from KEH exposure remaining relatively high. Therefore, for less complex products, the negative channel on performance is likely to outweigh the positive. For complex products, the number of linkages and possible combinations between product design and production rises considerably, implying a more ill-structured problem space, which increases the need to transfer tacit knowledge. When complexity is high, specialist knowledge embedded in pre-production activities become more difficult to appropriate and manipulate (Alnuaimi, & George, 2016). The negative impact from KEH is therefore less sensitive to an increase in product complexity. Hence, for complex products, the positive channel on performance is likely to outweigh the negative.

Based on this, we state our fourth hypothesis:

> ***H4.*** *Low levels of product complexity negatively moderate the relationship between vertical integration of pre-production activities and performance, while high levels of product complexity positively moderate this relationship.*

Regarding the integration of post-production activities, for less complex products, there are fewer knowledge interfaces and interactions between the production and post-production stage, implying a relatively well-structured problem space, which reduces the relative need to transfer tacit knowledge. At the same time, intricate understandings of customer preferences via post-production activities may be misused, hence the negative impact from KEH exposure remain relatively high. Therefore, for less complex products, the negative channel on performance is likely to outweigh the positive. For complex products, the logistical and distribution options to support production become more challenging to synchronise because of increased interlinkages between production and post-production (Bode and Wagner, 2015), increasing the relative need to transfer tacit knowledge. The explicit knowledge used in post-production activities, such as well-established industry practices and protocols, help to standardise interactions and mitigate strategic manipulation of knowledge (Lambert *et al.*, 1998), limiting the negative impact from KEH exposure as product complexity rises. Hence, for complex products, the positive channel on performance is likely to outweigh the negative.

Based on this, we state our fifth hypothesis:

> ***H5.*** *Low levels of product complexity negatively moderate the relationship between vertical integration of post-production activities and performance, while high levels of product complexity positively moderate this relationship.*

Regarding the integration of *both* pre- and post-production activities, for less complex products, there are fewer knowledge interfaces and potential interactions between the three stages of production implying relatively well-structured problem space, while the flow of knowledge across multiple stages grants greater scope for knowledge appropriation and manipulation. Therefore, for less complex products, the negative channel on performance is likely to outweigh the positive. For complex products, the linkages and possible combinations between all three stages rise considerably – likely more than that for integrating either pre- or post-production only. However, as product complexity rises, the negative impact from KEH is also likely to escalate considerably from the connection between the stages. For example, the post-production team may give undue weight to information about customers, leading to manufacturers of complex products who are excessively customer-oriented (Kirca *et al.*, 2005). The opposite case – of the pre-production team manipulating the knowledge accumulation process towards an excessive focus on technologically oriented designs, paying little heed to consumer preferences – is also possible (Christensen and Raynor, 2003).

Therefore, for more complex products, whether the net effect is positive or negative is difficult to determine a priori. We state hypotheses covering two scenarios. For situations where the premium to sharing tacit knowledge is particularly high, we state the first part of our sixth hypothesis as follows:

> ***H6a*** *Product complexity negatively moderates the relationship between the vertical*

integration of both pre- and post-production activities and performance.
For situations where the negative impact from KEH exposure is comparatively less, we state the second part of our sixth hypothesis:

H6b *Low levels of product complexity negatively moderate the relationship between vertical integration of both pre- and post-production activities and performance, while high levels of product complexity positively moderate this relationship.*

Whether H6a or H6b is the case, we defer to empirical examinations.

Figure 3 illustrates in graphical terms the moderating effect of product complexity on the relationship between vertical integration and performance, for the integration of three types of activity. The positive impact from enhanced knowledge transfer is compared to the negative impact from greater KEH exposure, resulting in the net effect on performance stated in our hypotheses.

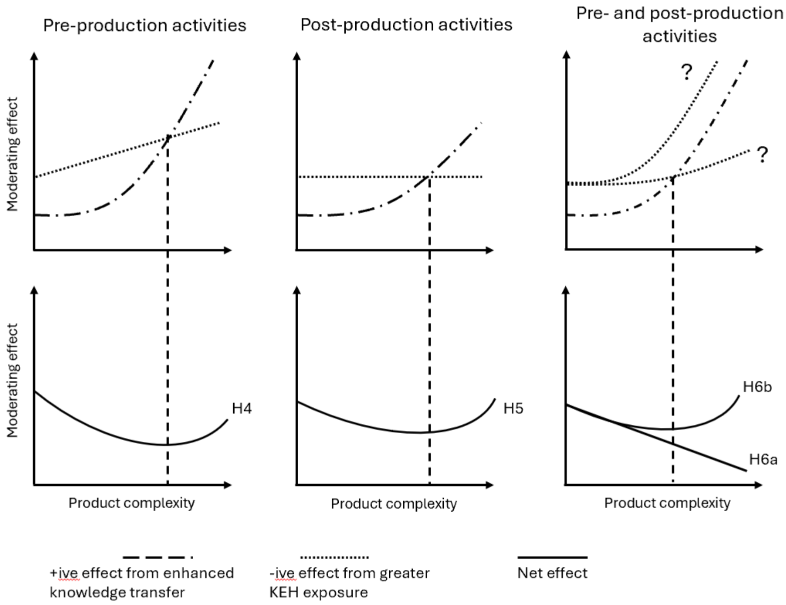

Figure 3. Product complexity's effect on the relationship between vertical integration and firm performance, for three types of integration (H4–H6b)

The summary of the set of hypotheses is illustrated in Figure 4 below. Product complexity functions as a moderating variable, whose net effect differ for low and high levels.

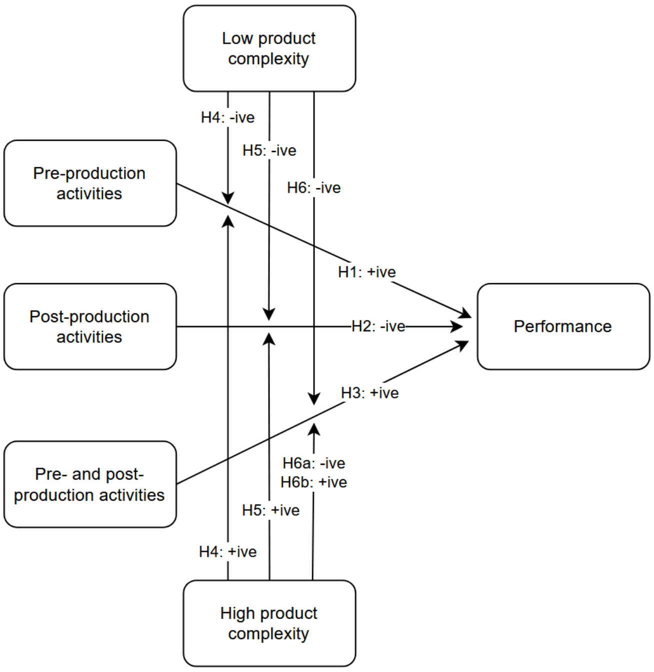

Figure 4. Summary of Hypotheses (H1–H6b)

4. Data and methods

4.1. Data source

Our main source of data comes from annual reports of UK manufacturing firms submitted to Companies House. We have developed dedicated Python scripts to extract key textual data from the report. The script processes each report line by line, searching for keywords pertaining to non-production activities, which are often found in the Directors' Report section that details many secondary activities and strategic shifts in business. We also examine Notes to the Financial Statements, which provide further disclosures, such as the breakdown of employees by activity or location. The focus on these two sections minimises the risk of extracting words out of context. We conduct data validation procedures, including consistency checks and outlier analysis, to ensure the accuracy of our data extraction. The approach is similar to that of Kharlamov and Parry (2021), who use text-mining techniques on firm descriptions in the FAME (Financial Analysis Made Easy) database. However, only a single-year snapshot per firm is accessible via FAME. By going directly to the source material each year, we overcome this limitation and construct a panel data set. This results in a sample of 7,740 firms.

This method offers several advantages over the more commonly used survey-based measures of vertical integration. First, UK firms are legally required under the Companies Act 2006 to submit annual reports, including financial statements and directors' or auditors' reports. This statutory requirement ensures significantly higher coverage and reliability compared to survey-based methods. Second, whereas survey data quality hinges on respondents' knowledge, which varies widely, our data set benefits from consistency, as the information is audited and board-approved according to company law. Third, our approach provides rich insights into firms' non-production activities, which are often not identifiable in balance sheets or profit and loss statements.

Our second source of data comes from the Harvard Growth Lab, specifically the Product Complexity Index (PCI) developed by Hidalgo and Hausmann (2009). The PCI assesses product complexity based on the diversity and sophistication of knowledge inputs required for production. This information is classified at the Harmonized System (HS), an international standard for categorising goods in global trade. The third source of our data is FAME, used to derive firm-level measures of productivity and to construct a range of control variables..

4.2. Variables

Using the data sources described in Section 4.1, we compute a number of variables that can be grouped into the following categories.

4.2.1. Dependent variable – productivity. We use productivity as a proxy for performance and measure productivity using total factor productivity (TFP) derived from a translog production function:

$$y_{it} = \beta_k k_{it} + \beta_l l_{it} + \beta_{kk} k_{it}^2 + \beta_{ll} l_{it}^2 + \beta_{kl} k_{it} l_{it} + \omega_{it} + \varepsilon_{it} \quad (1)$$

where y, k and l refer to the logarithms of value added, the number of employees and capital stock, respectively. The subscripts *i* and *t* denote firm and time, respectively. ω_{it} is a constant term and represents a firm productivity at time t. ε_{it}, on the other hand, is an i.i.d error term.

In order to avoid the correlation between input choices and ω_{it}, we compute the parameters using the Levinsohn–Petrin method, where intermediate inputs are used as a proxy for ω_{it} (Levinsohn and Petrin, 2003). Using consistent estimators of $\hat{\beta}_k, \hat{\beta}_l, \hat{\beta}_{kk}, \hat{\beta}_{ll}$ and $\hat{\beta}_{kl}$, we compute an estimate for $\widehat{\omega}_{it}$ that represents TFP:

$$\widehat{\omega}_{it} = y_{it} - \hat{\beta}_k k_{it} - \hat{\beta}_l l_{it} - \hat{\beta}_{kk} k_{it}^2 - \hat{\beta}_{ll} l_{it}^2 - \hat{\beta}_{kl} k_{it} l_{it} \quad (2)$$

We adopt the translog specification because it allows for flexible substitution patterns and non-constant elasticities of scale, accommodating potential heterogeneity in production technologies across firms. As a robustness check, we also estimate TFP using a Cobb-Douglas specificatiotn, and results are reported in Section 5.

4.2.2. Independent variable – vertical integration. As mentioned, we use Python text-mining techniques to compute measures of vertical integration. We begin by searching for key words of firms' secondary activities, separated into pre- and post-production. Pre-production activities correspond to the top panel of Table 2, while post-production activities correspond to the bottom panel. Different firms employ slight variants in terminology, such as "sale", "sales" or "retail", to denote similar activities. We therefore use a broad spectrum of word families and context-specific analysis to ensure that our identification of these activities is as precise and comprehensive as possible. Hence, the keywords in Table 2 also include not only the exact words but their variations.[1] After identifying firms' non-production activities, we classify firms based on vertical integration status by generating several dummy variables according to the categories in Table 3.

[1] In our Python-based search, we found words based on similarity, that is by calculating the similarity between two strings. This is helpful for capturing similar variations or corrupted words that arose during the conversion of documents. It also ensures that we capture not only the exact words but also their closely related forms in our search.

Table 2. List of pre- and post-production economic activities in manufacturing firms to support production

Pre-production activities	Design
	Research
	Development
	Engineering
	Prototype
Post-production activities	Distribution
	Logistics
	Storage
	Wholesale
	Retail
	Warehousing

Table 3. Binary (dummy) variables for different types of integration

Binary variables	Description
$TYPE1$	Standalone (non-integrated)
$TYPE2$	Pre-production only
$TYPE3$	Post-production only
$TYPE4$	Both pre- and post-production (fully integrated)

4.2.3. Control variables. We incorporate a set of control variables in our regression models. First, we include logged total assets (*LTASSET*) to capture the financial capacity of the firm, reflecting its capital-based scale (Teece, 1980, Acemoglu et al., 2009). Second, we incorporate the logged number of employees (*EMP*) as a proxy for firm size. The scale of a firm's workforce can be a critical factor in its decision to vertically integrate. Larger firms, with more extensive human resources, may opt for vertical integration to achieve greater control over operations and to streamline processes, capitalising on their size and associated benefits. Third, we include an export dummy variable (*EXP*), denoting whether the firm faces international competition. Exporting firms may adopt vertical integration in response to the unique challenges and opportunities presented by global markets, affecting both their productivity and integration strategies (Wagner, 2007). Fourth, we control for logged capital intensity (*KINTENSITY*), calculated as the ratio of capital to labour. This metric provides insights into a firm's resource use efficiency. Firms with higher capital intensity, suggesting greater reliance on physical capital over labour, might be more predisposed to vertical integration (Lafontaine and Slade, 2007).

4.2.4. Moderating variable – product complexity. In order to derive the PCI moderating variable at the firm level, we adapt an approach inspired by Acemoglu *et al.* (2010). PCI is only available at the four-digit industry level. In order to introduce firm-level variation, we incorporate additional indicators – specifically R&D intensity, or, if R&D data are missing (notably for Type 1 and Type 3 firms), capital intensity. This follows the premise, also suggested by Acemoglu *et al.* (2010), that firms investing more in R&D or capital are more likely to produce or manage complex products.

We begin by ranking each four-digit industry according to its PCI, from the highest to the lowest value. Next, firms within each industry PCI category are ranked based on their R&D intensity, or, if R&D data are unavailable, by their capital intensity. We then establish a pseudo-continuum of PCI values within each industry category by assigning a distinct PCI range to each rank. For a firm in rank *i*, we determine its upper and lower PCI bounds by referencing the PCI values of the immediately higher rank (*i-1*) and the immediately lower rank (*i+1*). The upper bound is set by adding half of the difference between the PCI values of ranks *i* and *i-1* to the PCI of rank *i*, while the lower bound is determined by subtracting half of the difference between the PCI values of ranks *i* and *i+1* from the PCI of rank *i*. [2] This method ensures that PCI values are not fixed at a single industry-wide level but instead vary within each category.[3] Once these bounds are established, firms within the same PCI rank are assigned values according to their relative R&D intensity, or, in the absence of R&D data, their capital intensity. By interpolating values in this way, we ensure that firms with the same rank do not receive the exact same PCI, but rather a nuanced value reflecting their relative R&D or capital intensity. Firms with greater R&D or capital intensity receive PCI values closer to the upper bound, while those with lower intensity receive those closer to the lower bound.

4.3. Data description

Within the time period of our study, Type 1 firms, characterised as standalone (non-integrated), constitute approximately 13% of the data set. Type 2 firms (pre-production only) represent a smaller segment of 7.3%. The most prevalent are Type 3 (post-production only) and Type 4 firms (both pre- and post-production), accounting for 38% and 42%, respectively. The FAME data set is biased towards large enterprises (Harris and Li, 2008), and it is therefore unsurprising that the representation of larger firms with greater resources leads to a large proportion of Type 4 (fully integrated) firms in our data set. Figure 5 shows how the distribution of different types of firm changes over time. There are no sudden shifts in the composition in any given year; rather, the changes are gradual but cumulative. We see that Type 4 firms have progressively replaced Type 3 firms as the most common type from about 2012 onwards, indicating an increasing propensity for integration across both pre- and post-production activities. By contrast, the proportion of Type 1 firms decreases from 15.6% in 2003 to 13.6% in 2019, which underscores a shift away from standalone (non-integrated) arrangements, consistent with the general trends observed in manufacturing towards servitisation and the diversification of activities (Baines *et al.*, 2009; Neely, 2008). For summary statistics of the variables, please refer to Table A3 in the Appendix. For a breakdown of these statistics by the four categories of firm, see Table A4, and for correlations between these variables, see Table A5.

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[2] Since the use of mid-points to establish PCI ranges is somewhat arbitrary, we verify the robustness of our results by testing alternative parameter values between 0 and 1, all of which yield consistent outcomes.

[3] In each year, there are top PCI and bottom PCI values for which we do not have PCI values immediately above or below to work out the mid-points to be added or subtracted. For these cases, we take the average spread across different PCI ranks and use half of that amount as the value to be added or subtracted from the top and bottom PCI values. While this midpoint is somewhat arbitrary, as above, using other reasonable parameter values still yields consistent results.

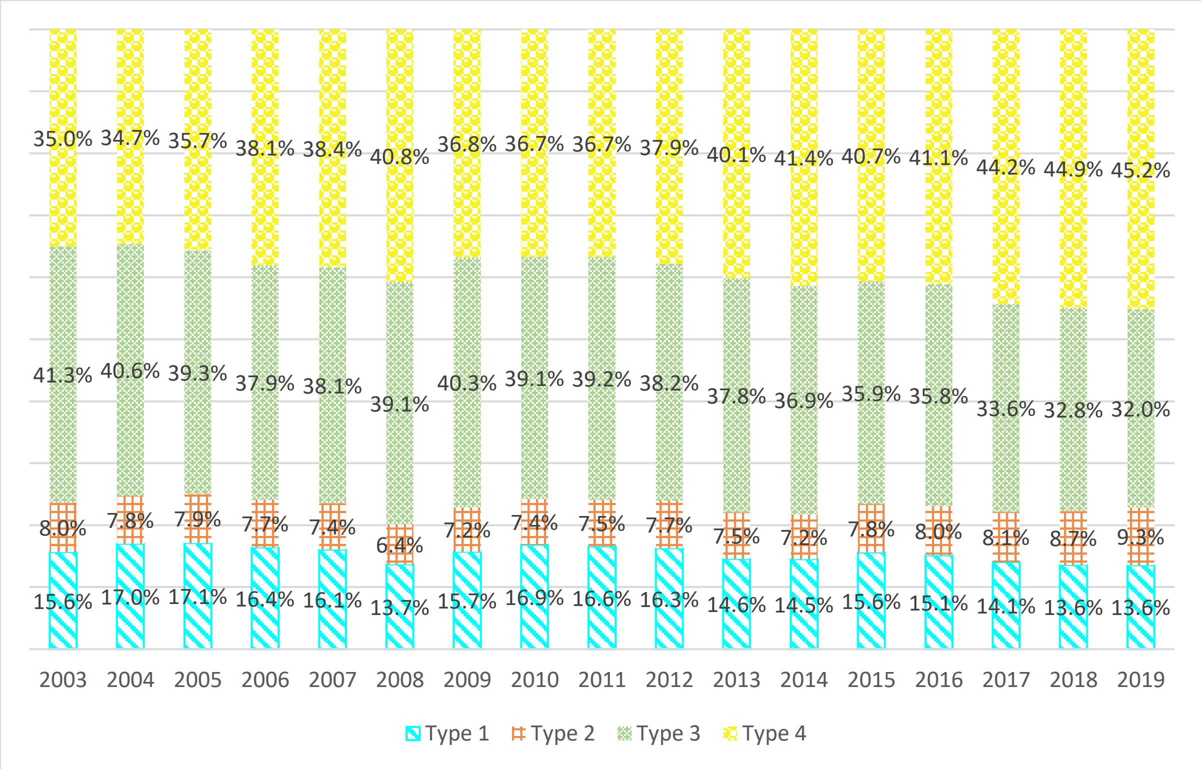

Figure 5. Proportion of different types of firms over time

We examine the pattern in the distribution of different types of firm across various manufacturing sub-sectors, which are presented in Table A6. A distinct pattern emerges from the data: in more technology-intensive sectors, such as the manufacture of computer, electronic and optical products (SIC 26) and electrical equipment (SIC 27), there is a marked decrease in the presence of standalone firms (Type 1) and a pronounced increase in integrated firms (Types 2, 3 and 4). For instance, in the electronics sector (SIC 26), standalone firms constitute only 7.1% of the total, whereas fully integrated firms (Type 4) account for a significant 60.4%. Similarly, in the electrical equipment sector (SIC 27), standalone firms represent 9.2%, while fully integrated firms make up 56.3%. Conversely, in less technology-intensive sectors, such as the manufacture of food products (SIC 10), standalone firms are more prevalent, comprising 18.9% of the total, which is higher than the overall average for Type 1 firms. This sector also exhibits a substantial presence of Type 3 firms (post-production only), accounting for 51.6% of the total, indicating the importance of in-house distribution and logistics activities in such industries.

The above pattern suggests that technological intensity favours more integrated business models, possibly because of the complex nature of production and the need for close alignment between pre- and post-production processes with core production capabilities. Less technologically intensive sectors, on the one hand, appear to benefit specifically from in-house post-production activities, which give them more direct access to their customers. Hence, this heterogeneity sheds light on the various strategic approaches regarding vertical integration adopted by firms in different sectors.

4.4. Methods

To empirically test H1–H3, we construct an econometric model to test the effect of different types of vertical integration on firm productivity. The equation is expressed below:

$$TFP_{ijt} = \beta_0 + \beta_1 TYPE2_{ijt} + \beta_2 TYPE3_{ijt} + \beta_3 TYPE4_{ijt} + X_{ijt} + \mathrm{IND}_j + \mathrm{TIME}_t + \varepsilon_{ijt} \quad (3)$$

TFP_{ijt} denotes the total factor productivity of firm i, in industry j at time t. $TYPE2$, $TYPE3$ and $TYPE4$ denote whether a firm belongs to each of these types of vertically integrated firm. X_{ijt} is the set of control variables. We also include industry fixed effects IND_j to capture any time-invariant industry j's characteristics that may affect firm productivity and TIME_t to capture macro effects at time t. ε_{ijt} is the error term.

We employ a fixed effects (FE) estimator to account for time-invariant unobserved heterogeneity, focusing on within-firm variation. This allows us to examine how changes in integration types correlate with changes in productivity within the same firm over time. We also employ the Arellano–Bond generalised method of moments (GMM) estimator to mitigate potential endogeneity bias, such as those arising from reverse causality and omitted variables. This method uses lagged values as instruments, providing a dynamic framework to address the possible endogeneity between vertical integration and productivity. All standard errors are cluster-robust to account for within-group correlation in error terms.

To empirically test H4–H6, Equation (3) is modified as below:

$$TFP_{ijt} = \beta_0 + \beta_1 TYPE2_{ijt} + \beta_2 TYPE3_{ijt} + \beta_3 TYPE4_{ijt} + \beta_4 PCI_{jt} + \beta_5 PCI_{jt} TYPE2_{ijt} + \beta_6 PCI_{jt} TYPE3_{ijt} + \beta_7 PCI_{jt} TYPE4_{ijt} + \beta_8 PCI_{jt}^2 + \beta_9 PCI_{jt}^2 TYPE2_{ijt} + \beta_{10} PCI_{jt}^2 TYPE3_{ijt} + \beta_{11} PCI_{jt}^2 TYPE4_{ijt} + X_{ijt} + \mathrm{IND}_j + \mathrm{TIME}_t + \varepsilon_{ijt} \quad (4)$$

The coefficient β_4 captures the effect of product complexity on TFP, while coefficients β_5, β_6 and β_7 capture the moderating effects on different types of vertical integration. We include the squared terms to capture the non-linear moderating effects of PCI. Hence, the coefficient β_8 captures the effect of PCI squared on productivity, while the squared effects on the interaction between PCI and various types of vertical integration are shown by coefficients β_{9-11}. As before, we apply both the FE and the GMM estimator to account for potential endogeneity.

5. Results

Table 4 presents the regression results for Equation (3) in Model (1), using both the FE and GMM estimator. We treat Type 1 (standalone firms) as the baseline in all models. For Type 2 (pre-production only), the coefficient (β_1) is positive and statistically significant in both FE and GMM, indicating a consistent positive relationship between pre-production integration and productivity, thereby supporting H1. For Type 3 (post-production only), both the FE and GMM models now yield negative coefficients for β_2, though neither is statistically significant. When PCI interactive terms are included in Model (2) and Model (3), the coefficients become substantially larger and significant, which suggests partial support for H2. For Type 4 (both pre- and post-production), the coefficient (β_3) is positive and significant across both models, consistently suggesting that more comprehensive integration enhances productivity; this supports H3.

Model (2) adds the PCI and its interactions with Types 2, 3 and 4. In both FE and GMM, PCI itself is negative and significant, aligning with prior research highlighting the coordination challenges associated with increasing complexity. Among the interaction terms, only Type 3 × PCI is statistically significant and positive. Model (3) in Table 5 further introduces the squared term for PCI, which is also negative and significant. With both PCI and PCI^2 negative, the *ceteris paribus* effect of rising complexity on productivity appears to be consistently detrimental, possibly at an increasing rate. However, the interaction terms of Type 2 × PCI^2 and Type 3 × PCI^2 are positive and significant, suggesting that as complexity reaches higher levels, the negative effect can be partially offset for firms integrating pre- or post-production alone. By contrast, Type 4 × PCI^2 is insignificant, implying that for more comprehensively integrated firms, the advantages and disadvantages at higher complexity may cancel each other out. These results indicate that H4 and H5 are supported, but neither H6a nor H6b are supported. A summary of the hypotheses supported by our results is presented in Table 5.

Table 4. Regression results of Equations (3)–(5)

	(1) FE	(1) GMM	(2) FE	(2) GMM	(3) FE	(3) GMM
TYPE2	.009**	.008***	.009**	.012***	.004	.008
	(.004)	(.003)	(.004)	(.003)	(.004)	(.007)
TYPE3	-.001	-.003	-.001	-.011**	-.005*	-.013**
	(.003)	(.002)	(.003)	(.005)	(.003)	(.005)
TYPE4	.013***	.004**	.014***	.023***	.012***	.025***
	(.004)	(.002)	(.003)	(.005)	(.004)	(.006)
EMP	.276***	.054***	.289***	.098***	.289***	.095***
	(.017)	(.007)	(.017)	(.013)	(.003)	(.012)
LTASSET	.028***	.022***	.033***	.045***	.033***	.044***
	(.006)	(.004)	(.006)	(.007)	(.002)	(.007)
EXP	.022***	-.002	.022***	.015*	.022***	.017**
	(.004)	(.003)	(.004)	(.008)	(.002)	(.007)
KINTENSITY	-.019***	-.008**	-.021***	-.025***	-.021***	-.025***
	(.006)	(.003)	(.006)	(.007)	(.003)	(.006)
L.TFP	-	.828***	-	.682***	-	.689***
		(.019)		(.031)		(.029)
PCI	-	-	-.021***	-.156**	-.018***	-.149**
			(.006)	(.068)	(.006)	(.061)
PCI^2	-	-	-	-	-.018***	-.022***
					(.004)	(.002)
TYPE2* x *PCI	-	-	.009	.004	.006	.007
			(.006)	(.003)	(.007)	(.005)
TYPE3* x *PCI	-	-	.011***	.054***	.009**	.023***
			(.004)	(.007)	(.004)	(.007)
TYPE4* x *PCI	-	-	.004	.022	.006	.021
			(.004)	(.015)	(.005)	(.024)
TYPE2* x *PCI^2	-	-	-	-	.015**	.025***
					(.007)	(.005)
TYPE3* x *PCI^2	-	-	-	-	.012***	.028***
					(.004)	(.005)
TYPE4* x *PCI^2	-	-	-	-	.005	.018
					(.005)	(.012)
Constant	3.692***	.461***	3.644***	.891***	3.651***	.932***
	(.062)	(.061)	(.011)	(.104)	(.062)	(.095)
N	63,149	52,777	60,510	50602	60,510	50,601
AR(2) p-value	-	0.881	-	0.488		0.419
Hansen J p-value	-	0.352	-	0.187		0.288

*** $p < .01$, ** $p < .05$, * $p < .1$

Table 5. Summary of whether result supports each hypothesis

Hypothesis	Hypothesis summary	Supported?
H1	VI of pre-production activities positive association with performance	Yes
H2	VI of post-production activities negative association with performance	Partially
H3	VI of *both* pre- and post-production activities positive association	Yes
H4	Low levels of product complexity negatively moderate the relationship identified in H1, while high levels of product complexity positively moderate that relationship	Yes
H5	Low levels of product complexity negatively moderate the relationship identified in H2, while high levels of product complexity positively moderate that relationship	Yes
H6a/H6b	Product complexity negatively moderates the relationship identified in H3/ Low levels of product complexity negatively moderate the relationship identified in H3, while high levels of product complexity positively moderate that relationship	No

We perform several robustness checks to ensure the validity of our results. First, we test whether our results hold using alternative measures of productivity. Table 6 presents GMM estimations, where we replace TFP (from a translog production function) with labour productivity (Columns 1–3) and TFP from a Cobb–Douglas production function (Columns 4–6) as the dependent variable. We use the same set of control variables in our main sepcifications (Table 4). Across both alternative measures, the results remain qualitatively consistent with our main findings in Table 4.

We further assess robustness by excluding firms that may introduce classification biases. Table 7 reports GMM estimations after removing firms with subsidiaries (Columns 1–3), as these firms may attribute subsidiary activities as principal activities, potentially distorting the classification of vertical integration. After their exclusion, the qualitative results remain unchanged, indicating that the initial findings were not driven by such a misclassification. Additionally, we exclude firms in the "Repair and Installation of Machinery and Equipment" sector (SIC 33), a sector often considered more service-oriented than manufacturing (Columns 4–6 in Table 6). Again, the results remain consistent, suggesting that including or excluding this sector does not materially affect our conclusions. Across all robustness checks, the AR(2) p-values remain non-significant, indicating no second-order autocorrelation in the residuals, and the Hansen J tests confirm that the instruments used in GMM remain valid. These findings affirm that our conclusions regarding vertical integration, product complexity and their interactions are not sensitive to different measures of productivity or sample composition.

Table 6. Regression results using alternative measures of productivity as dependent variables

	Labour productivity as DV			TFP Cobb–Douglas production function as DV		
	(1) GMM	(2) GMM	(3) GMM	(4) GMM	(5) GMM	(6) GMM
TYPE2	.007**	.017***	.003	.011***	.021***	.004
	(.003)	(.004)	(.004)	(.003)	(.006)	(.003)
TYPE3	-.003	-.014**	-.012**	-.007	-.012***	-.011***
	(.002)	(.006)	(.005)	(.005)	(.004)	(.003)
TYPE4	-.010***	.033***	.045***	.012***	.022***	.024***
	(.002)	(.009)	(.012)	(.002)	(.006)	(.006)
TYPE2* x *PCI		.007	.012		.017	.006
		(.005)	(.012)		(.019)	(.005)
TYPE3* x *PCI		.031***	.019***		.024***	.008**
		(.010)	(.006)		(.007)	(.003)
TYPE4* x *PCI		.013	.004		.011	.019
		(.015)	(.006)		(.009)	(.014)
TYPE2* x *PCI^2			.027***			.031***
			(.009)			(.009)
TYPE3* x *PCI^2			.021***			.011***
			(.009)			(.003)
TYPE4* x *PCI^2			.012			.011
			(.015)			(.009)
Controls	Y	Y	Y	Y	Y	Y
N	52,777	50,602	50,601	52,777	50,602	50,601
AR(2) p-value	0.412	0.278	0.327	0.323	0.412	0.311
Hansen J p-value	0.339	0.123	0.186	0.199	0.141	0.228

*** p <.01, ** p <.05, * p <.1

Table 7. Regression results excluding certain types of firm

	Excluding firms that have subsidiaries			Excluding firms in "Repair and installation of machinery and equipment" (SIC 33)		
	(1) GMM	(2) GMM	(3) GMM	(4) GMM	(5) GMM	(6) GMM
$TYPE2$	.011***	.027***	.018*	.007**	.012***	.008
	(.003)	(.007)	(.010)	(.003)	(.003)	(.007)
$TYPE3$	-.007	-.024***	-.008***	-.003	-.011**	-.013**
	(.005)	(.006)	(.002)	(.001)	(.005)	(.005)
$TYPE4$	.012***	.043***	.049***	.010***	.023***	.025***
	(.002)	(.009)	(.008)	(.002)	(.005)	(.006)
TYPE2* x *PCI		.017	.006		.004	.007
		(.013)	(.005)		(.003)	(.005)
TYPE3* x *PCI		.048***	.028***		.054***	.023***
		(.010)	(.005)		(.007)	(.007)
TYPE4* x *PCI		-.023	-.010		.022	.021
		(.018)	(.008)		(.015)	(.024)
TYPE2* x *PCI^2			.012***			.025***
			(.003)			(.005)
TYPE3* x *PCI^2			.014***			.028***
			(.003)			(.005)
TYPE4* x *PCI^2			.012			.018
			(.011)			(.012)
Controls	Y	Y	Y	Y	Y	Y
N	34,060	32,440	32,440	50,689	50602	50,601
AR(2) p-value	0.648	0.317	0.451	0.588	0.488	0.419
Hansen J p-value	0.226	0.234	0.291	0.204	0.187	0.288

6. Discussion

Our results indicate that the type of business activities that firms integrate can influence performance. In general, integrating pre-production activities such as R&D and design is performance-enhancing, but there is little evidence to suggest that integrating post-production activities (on their own) such as logistics and wholesale is performance-enhancing, which may even negatively impact performance. Our results demonstrate that integrating *both* pre- and post-production activities has an even greater performance-enhancing effect than pre-production activities alone, suggesting significant complementarities when both pre- and post-production activities are combined to support core production capabilities. This is consistent with studies that report stronger performance improvement from between-stage integration than within-stage (Brandt *et al.*, 2022; Peyrefitte and Golden, 2004).

The moderating effect of product complexity exhibits a U-shaped relationship for *either* pre- or post-production activities. This implies that higher complexity alters the nature of the problem to become more ill-structured. This applies to both pre- and post-production activities irrespective of whether the problem is ill- or well-structured problems. However, for *both* pre- and post-production activities, we fail to find any significant moderating effect from product complexity. This suggests that for firms that integrate both sets of activities, the benefits derived from knowledge sharing are already subsumed within the diverse scope of functions in a "rugged" problem terrain where interdependencies of choices lead to complexity in choosing an optimal outcome (Levinthal, 1997; Nickerson and Zenger, 2004). For such firms whether they produce less complex or more complex products should not materially affect the gains from vertical integration.

Our results are robust to different measures of the dependent variable, the exclusion of certain samples, as well as attempts to account for possible endogeneity via GMM models.

6.1. Contributions to theory

Our study makes three main contributions to theory. First, we contribute to the transaction cost economics and knowledge-based view debate, focusing on the role of knowledge exchange hazards as the primary driver of vertical integration choices and firm performance (Heiman and Nickerson, 2002). By emphasising activities rather than value chain, our theoretical framework explains the trade-off between the more efficient transfer of tacit knowledge espoused by the KBV and greater exposure to KEH, rooted in the TCE understanding. Our framework identifies key linkages between manufacturing processes relevant to the context of modern manufacturing, where knowledge assets play a vital role in production. This presents a holistic view of manufacturing firms not simply as producers of particular products but rather as a nexus of interrelated functions converging around a set of core production capabilities. Knowledge flows between activities influence how effectively production capabilities can be leveraged. This sheds light on potential synergies between various manufacturing activities, indicating that complementary – heterogenous – assets are more performance-enhancing than supplementary – similar – assets, in line with consensus among the RBV (Buckley *et al.*, 2009).

Second, our study begins to probe into the effects of product complexity on vertical integration. We contribute to understanding the connection between product and knowledge complexity in the manufacturing context. To the best of our knowledge, this is the first study to do so. The finding of a U-shaped moderating relationship on vertical integration and performance suggests that, as product complexity increases, the returns to knowledge sharing via integration also rise. Complex products concern more ill-structured problems, benefiting from the efficient transfer of tacit knowledge facilitated by vertical integration (Nickerson and Zenger, 2004; Jacobs and Swink, 2011). However, the boundary condition is that this applies to integrating *either* pre- or post-production activities, but not both – in line with findings from network RBV, where strategic alliances tend to be preferred over outright ownership for complex problems (Grant and Baden-fuller, 2004; Stuart *et al*., 2009).

Third, we shed light on the supply chain management literature. Our activity-based conceptualisation of vertical integration analyses the complexity of supply chains in the context of product complexity. Our results, for example, suggest that post-production activities and customised production are complementary, enabling greater supply chain agility to respond to a larger number of customisable options, as often seen in complex products (Braunscheidel and Suresh, 2009). Sophisticated supply chain relationships often emerge around the manufacturing of complex products, and it is rare to find a single firm that engages in the full spectrum of activities (Hobday, 1998; Hobday *et al.*, 2000). Consequently, this points to the limits of vertical integration and that some degree of specialisation may be optimal for highly complex products. Therefore, from the supply chain perspective, firms should branch out into pre- or post-production, but not both (Rothaermel *et al.*, 2006; Santos and Eisenhardt, 2005), parallelling the specialisation from the product perspective where high-tech products should be either technology- or customer-oriented, but not both (Christensen and Raynor, 2003). We thus contribute to an understanding of the relationship between different dimensions of complexity, at the supply chain and the product levels.

6.2. Implications for practice

The practical implications of our findings are that firms should develop a strong awareness of the complexity of knowledge required to manufacture their products. In most cases, firms should strive to integrate both knowledge-intensive pre-production activities, such as R&D,

and post-production activities, such as wholesale and delivery. Having access to the full spectrum of activities can greatly complement firms' core production capabilities, especially since detailed knowledge of customers and markets acquired through post-production activities can feed back to advance product designs and production. For complex products, however, the evidence points to the need for very complex knowledge input, which may be beyond the abilities of any single firm. In such situations, the optimal strategy may be to choose to integrate *either* pre-production or post-production, while partnering with firms with different resources.

6.3. Limitations and future research

Despite our best attempts, the study has some limitations. First, our measure of vertical integration, though novel, remains relatively aggregate. Future studies should try to break down the data into more detailed definitions to allow a richer classification of vertical integration by type. Our measure is essentially one of vertical integration scope, and such measures can be greatly enhanced by augmenting them with measures of vertical integration intensity (Gilley and Rasheed, 2000). Second, our findings are based on a sample of UK firms, and how generalisable our conclusions are to other countries remains to be seen. For example, the results may be different in the context of a developing country (Li *et al.*, 2017).

7. Conclusion

Our study examines the relationship between vertical integration and performance across manufacturing firms in the UK over the 2003–19 period. We devise a theoretical framework of vertical integration that focuses on activities that support firms' core production and corresponding knowledge requirement, particularly the effective transfer of tacit knowledge. Using a novel computational approach that analyses large volumes of information found in company annual reports, we find that the integration of pre-production activities, and of *both* pre- and post-production activities, is positively associated with firm-level performance, but not the integration of post-production activities alone. Product complexity appears to moderate the relationship between vertical integration and performance in a U-shaped manner.

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Appendix

Table A1. Frequency of each type of firm

Binary variables	Description	Frequency	Percent (%)
$TYPE1$	Standalone (non-integrated)	8,168	12.93%
$TYPE2$	Integrated pre-production	4,583	7.78%
$TYPE3$	Integrated post-production	23,693	37.52%
$TYPE4$	Integrated pre- and post-production	26,706	42.29%
$TYPE2 + TYPE3 + TYPE4$	Integrated in any way	54,982	87.59%

Table A2. Percentage of each type of firm averaged for each year (2003–19)

Year	$TYPE1$	$TYPE2$	$TYPE3$	$TYPE4$	N
2003	15.63	8.04	41.33	34.98	3,133
2004	16.97	7.78	40.55	34.68	3,134
2005	17.12	7.91	39.30	35.65	3,259
2006	16.42	7.66	37.85	38.05	3,471
2007	16.07	7.43	38.07	38.40	3,632
2008	13.69	6.44	39.08	40.77	3,958
2009	15.68	7.21	40.30	36.79	4,935
2010	16.85	7.36	39.07	36.69	5,292
2011	16.59	7.48	39.19	36.72	5,585
2012	16.26	7.70	38.16	37.85	5,735
2013	14.58	7.47	37.80	40.13	5,870
2014	14.51	7.21	36.90	41.36	6,054
2015	15.62	7.78	35.93	40.65	6,297
2016	15.13	7.96	35.76	41.13	6,218
2017	14.05	8.06	33.63	44.24	5,928
2018	13.57	8.69	32.78	44.94	5,865
2019	13.56	9.26	31.96	45.20	5,743

Table A3. Summary statistics of key variables

	Mean	s.d	Min	Max	N
TFP	3.94	0.55	-0.56	11.46	
TYPE1	0.13	0.34	0	1	
TYPE2	0.07	0.26	0	1	
TYPE3	0.38	0.48	0	1	
TYPE4	0.42	0.49	0	1	63,150
EMP	4.62	1.18	0	10.34	
LTASSET	7.54	1.99	-6.91	16.27	
EXP	0.60	0.24	0	1	
KINTENSITY	2.77	1.34	-8.85	11.36	

Table A4. Summary statistics broken down by each type of firm

Binary variable	Description	N	Mean	SD
$TYPE1$	Sales	8,168	9.42	1.39
	Value-added	8,083	8.17	1.31
	Employee	8,168	4.31	1.24
	Capital	8,168	7.03	2.08
	TFP	8,168	4.98	0.91
$TYPE2$	Sales	4,583	9.70	1.30
	Value-added	4,529	8.60	1.22
	Employee	4,583	4.67	1.12
	Capital	4,583	7.42	1.83
	TFP	4,583	5.08	0.87
$TYPE3$	Sales	23,693	9.71	1.22
	Value-added	23,434	8.33	1.19
	Employee	23,693	4.41	1.15
	Capital	23,693	7.17	2.01
	TFP	23,693	5.09	0.91
$TYPE4$	Sales	26,706	10.07	1.29
	Value-added	26,386	8.88	1.26
	Employee	26,706	4.88	1.13
	Capital	26,706	7.69	1.89
	TFP	26,706	5.25	0.91

Table A5. Correlation matrix of variables

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) ***TFP***	1.000								
(2) ***TYPE1***	-0.036***	1.000							
(3) ***TYPE2***	-0.021***	-0.108***	1.000						
(4) ***TYPE3***	0.031***	-0.299***	-0.217***	1.000					
(5) ***TYPE4***	0.005	-0.330***	-0.239***	-0.663***	1.000				
(6) ***EMP***	-0.031***	-0.097***	0.013***	-0.136***	0.193***	1.000			
(7) ***LTASSET***	-0.006	-0.082***	0.004	-0.101***	0.153***	0.751***	1.000		
(8) ***EXP***	0.021***	-0.100***	0.018***	-0.093***	0.149***	0.063***	0.047***	1.000	
(9) ***KINTENSITY***	-0.003	0.006	-0.002	0.002	-0.005	-0.014***	-0.043***	-0.007*	1.000

*, ** and *** indicate significance level at 10%, 5% and 1%, respectively.

Table A6. Percentage of each type of firm in various industries

SIC	Description	$TYPE1$	$TYPE2$	$TYPE3$	$TYPE4$	N
10	Manufacture of food products	18.92	4.14	51.64	25.27	9,067
11	Manufacture of beverages	14.54	2.09	62.24	20.23	1,176
13	Manufacture of textiles	23.01	6.48	43.60	26.89	1,651
14	Manufacture of wearing apparel	21.05	2.41	50.73	25.79	1,159
15	Manufacture of leather and related products	12.88	2.57	54.63	29.89	194
16	Manufacture of wood and of products of wood and cork, except furniture	25.98	4.07	54.32	15.61	1,620
17	Manufacture of paper and paper products	17.88	5.49	49.08	27.54	2,567
19	Manufacture of coke and refined petroleum products	15.43	6.67	45.26	32.63	285
20	Manufacture of chemicals and chemical products	11.20	7.12	34.16	47.50	5,660
21	Manufacture of basic pharmaceutical products and pharmaceutical preparations	9.45	8.00	31.72	50.81	1,724
22	Manufacture of rubber and plastic products	14.86	6.80	41.37	36.94	5,757
23	Manufacture of other non-metallic mineral products	19.10	4.34	47.61	28.93	2,094
24	Manufacture of basic metals	21.98	9.34	39.14	29.52	2,151
25	Manufacture of fabricated metal products, except machinery and equipment	18.87	10.91	31.68	38.52	11,785
26	Manufacture of computer, electronic and optical products	7.10	9.12	23.38	60.38	5,392
27	Manufacture of electrical equipment	9.19	8.61	25.83	56.34	4,513
28	Manufacture of machinery and equipment n.e.c	10.00	10.96	25.97	53.05	8,493
29	Manufacture of motor vehicles, trailers, and semi-trailers	14.04	10.64	27.12	48.18	2,706
30	Manufacture of other transport equipment	13.69	12.94	25.30	48.05	1,723
31	Manufacture of furniture	16.53	4.61	49.50	29.34	2,123
32	Other manufacturing	14.34	7.63	37.71	40.30	12,294
33	Repair and installation of machinery and equipment	23.77	5.32	47.37	23.52	3,928