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Revisiting Marshall's Agglomeration Economies: Technological Relatedness and the Evolution of the Sheffield Metals Cluster

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Revisiting Marshall's Agglomeration Economies: Technological Relatedness and the Evolution of the Sheffield Metals Cluster

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POTTER A. and WATTS H. D. Revisiting Marshall's agglomeration economies: technological relatedness and the evolution of the Sheffield metals cluster, *Regional Studies*. According to Alfred Marshall, firms receive increasing returns from a trinity of agglomeration economies: a local pool of skilled labour, local supplier linkages and local knowledge spillovers. This article re-examines the mechanisms underlying Marshall's agglomeration economies in the Sheffield metals cluster wherein Marshall discovered them. Despite the cluster's decline, empirical evidence is found that the mechanisms underlying Marshallian agglomeration economies continue to occur within the surviving metals industry. However, upon closer examination, Marshallian agglomeration economies have evolved to become more prevalent amongst plants that use related metals technology. The results highlight the importance of technological relatedness to cluster survival.

Evolutionary economic geography Technological relatedness Agglomeration economies Cluster Industrial district Alfred Marshall

POTTER A. and WATTS H. D. 对马歇尔集聚经济的再思考：技术相关性和谢菲尔德金属产业集群的演化，*区域研究*。根据阿弗里德·马歇尔的研究，企业可通过由集聚经济所带来的充足的熟练劳动力、本地供应商和知识溢出而获得报酬递增。本文调研了马歇尔发现集聚经济这一理论的谢菲尔德金属产业集群，重新考察了马歇尔集聚经济的内在机理。虽然产业集群已经衰落，但证据表明马歇尔集聚经济的内在机理仍然存在于现有的金属产业中。然而进一步的研究表明，马歇尔集聚经济在使用了相关金属技术的企业中体现的更为明显。这一结论强调了集群生存的技术相关性。

演化经济地理学 技术相关性 集聚经济 集群 工业区 阿弗里德·马歇尔

POTTER A. et WATTS H. D. Réévaluer les économies d'agglomération d'après Marshall: la connexité technologique et l'évolution du cluster des métaux à Sheffield, *Regional Studies*. Selon Alfred Marshall, les entreprises jouissent des rendements croissants grâce à trois sources d'économies d'agglomération: à savoir, un bassin local de main-d'oeuvre qualifiée, des relations interindustrielles locales et des retombées de la connaissance locales. Cet article cherche à réévaluer les mécanismes qui étayent les économies d'agglomération d'après Marshall pour ce qui est du cluster des métaux à Sheffield où Marshall les a découvertes. Malgré le déclin du cluster, les preuves empiriques laissent voir que les mécanismes qui étayent les économies d'agglomération d'après Marshall ne cesse de se présenter au coeur de l'industrie des métaux qui a réussi à survivre. Cependant, lorsque l'on les examine de plus près, il s'avère que les économies d'agglomération d'après Marshall ont évolué et sont plus présentes parmi les établissements qui utilisent une technologie liée à l'industrie des métaux. Les résultats soulignent l'importance de la connexité technologique pour la survie du cluster.

Géographie économique évolutionnaire Connexité technologique Économies d'agglomération Cluster District industriel Alfred Marshall

POTTER A. und WATTS H. D. Ein frischer Blick auf die Marshall'schen Agglomerationswirtschaften: technische Verwandtschaft und die Entwicklung des Metallindustrie-Clusters von Sheffield, *Regional Studies*. Laut Alfred Marshall erzielen Firmen steigende Erträge durch eine Kombination aus drei Agglomerationswirtschaften: ein lokales Angebot an qualifizierten Arbeitskräften, Verbindungen zu lokalen Zulieferern und lokale Wissensübertragungen. In diesem Beitrag werfen wir einen frischen Blick auf die Mechanismen hinter den Marshall'schen Agglomerationswirtschaften im Cluster der Metallindustrie von Sheffield, wo Marshall die Mechanismen auch entdeckt hatte. Trotz des Niedergangs dieses Clusters finden wir empirische Belege dafür, dass die Mechanismen hinter den Marshall'schen Agglomerationswirtschaften in der überlebenden Metallindustrie weiterhin auftreten. Bei näherer Betrachtung stellt sich jedoch heraus, dass sich die Marshall'schen Agglomerationswirtschaften weiterentwickelt haben

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und heute unter Betrieben prävalenter sind, die verwandte Metalltechniken einsetzen. Die Ergebnisse verdeutlichen die Bedeutung von technischer Verwandtschaft für das Überleben eines Clusters.

Evolutionäre Wirtschaftsgeografie Technische Verwandtschaft Agglomerationswirtschaften Cluster Industriebezirk Alfred Marshall

POTTER A. y WATTS H. D. Revisión de economías de aglomeración *marshallianas*: relación tecnológica y evolución de la aglomeración metalúrgica en Sheffield, *Regional Studies*. Según Alfred Marshall, las empresas reciben ventajas crecientes a través de una combinación de tres economías de aglomeración: un fondo local de trabajadores cualificados, vínculos con proveedores locales y desbordamientos de conocimiento local. En este artículo reexaminamos los mecanismos detrás de las economías de aglomeración *marshallianas* en la agrupación de la industria metalúrgica de Sheffield donde las descubrió Marshall. Pese al declive de la aglomeración, observamos datos empíricos de que los mecanismos detrás de las economías de aglomeración *marshalliana* siguen ocurriendo en la industria metalúrgica que ha sobrevivido. Sin embargo, al examinarlo más detenidamente, observamos que las economías de aglomeración *marshallianas* han evolucionado y hoy día están más presentes en las plantas que utilizan tecnología relacionada con metales. Los resultados destacan la importancia de las relaciones tecnológicas para la supervivencia de las aglomeraciones.

Geografía económica evolutiva Relación tecnológica Economías de aglomeración Aglomeración Comarca industrial Alfred Marshall

JEL classifications: O18, R11, R12, R58

INTRODUCTION

> When an industry has thus chosen a location for itself, it is likely to stay there long: so great are the advantages which people following the same skilled trade get from near neighborhood to one another. The mysteries of the trade become no mysteries; but are as it were in the air ….
> (MARSHALL, 1890, p. 225)

Why do firms agglomerate in close geographical proximity? To answer this question, many turn to the classical economist Alfred Marshall and the agglomeration theory he developed over one hundred years ago (KRUGMAN, 1991; PORTER, 1998; BECATTINI, 2006). MARSHALL (1890) was the first scholar to argue that firms experience external economies and increasing returns when they agglomerate together in close geographical proximity (MARTIN, 2006). Specifically, MARSHALL (1890) identified three mechanisms – the so-called trinity of agglomeration economies – that generate increasing returns in agglomerations: a local pool of skilled labour, local supplier linkages and local knowledge spillovers. Traditionally, these Marshallian agglomeration economies are regarded as localization economies that occur when similar plants from the same industry cluster together in close spatial proximity.

Since the 1980s, MARSHALL's (1890) agglomeration theory and his thoughts on the localization of industry have undergone a substantial revival and he remains one of the most cited authors in the regional development literature (Fig. 1) (MARTIN, 2006). His ideas now play a central role in a variety of theories and policies, including Marshallian industrial districts (PIORE and SABEL, 1984; HARRISON, 1992; MARKUSEN, 1996; BECATTINI, 2006), New Economic Geography models (KRUGMAN, 1991; FUJITA *et al.*, 1999), industrial cluster policies (PORTER, 1998), local knowledge spillovers (JAFFE *et al.*, 1993), the Marshall–Arrow–Romer (MAR) externality (GLAESER *et al.*, 1992), and endogenous growth theory (ROMER, 1986). As MARSHALL's (1890) agglomeration theory continues to be at the heart of recent debates within regional studies, an interesting, yet unanswered, research question is whether Marshall's agglomeration economies are confined to industry-specific localization economies or whether they can also influence plants that specialize in related technologies (BOSCHMA and FRENKEN, 2011a; NEFFKE *et al.*, 2011a). Recent research within Evolutionary Economic Geography has begun to explore the role that technological relatedness plays in the evolution of firms, agglomerations, networks, industries and regions (FRENKEN and BOSCHMA, 2007; BOSCHMA and FRENKEN, 2011b). This research had found that at the start of the industry life cycle the interactions between technologically related industries can lead to the birth and evolution of new technologies, new product innovations, new technological niches and even entirely new industries through a process called regional branching (BOSCHMA and FRENKEN, 2006). As the industry grows, technological relatedness plays another central role by increasing the survival chances of those firms and spinoffs with pre-experience with technology from related industries (BOSCHMA and WETERINGS, 2007; KLEPPER, 2007; NEFFKE *et al.*, 2012).

However, comparatively little is known about the role that technological relatedness plays within the context of a declining industrial agglomeration during the later stages of the industry life cycle. Whilst some studies have begun to explore the relationship between technological relatedness and Marshallian agglomeration economies (NEFFKE *et al.*, 2012), few have studied this relationship amongst plants within a city-region that contains a declining industrial cluster. Technological relatedness is likely to play a crucial role when an industry

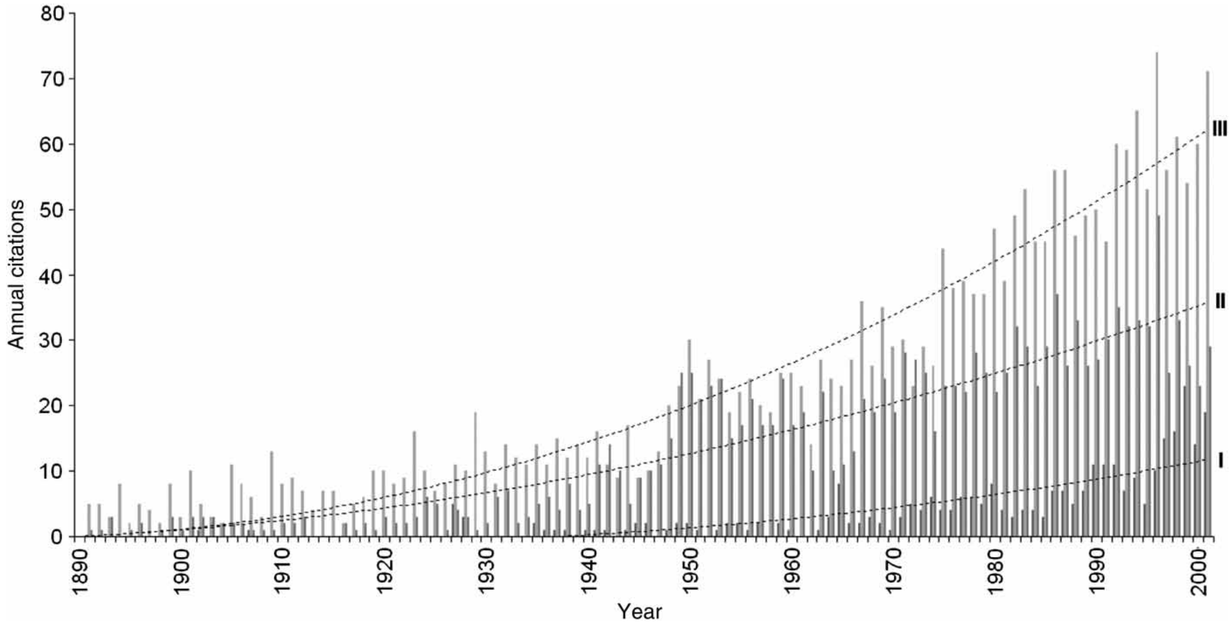

Fig. 1. The exponential growth of M*ARSHALL's (1890) agglomeration theory*
Note: Annual citation trend lines: I, agglomeration; II, industrial atmosphere; and III, industrial district
Source: Data are from JSTOR (1890–2001) (http://www.jstor.org/)

matures and eventually declines because it enables many plants to adapt and survive by diversifying into technologically related industries (GRABHER, 1993). However, it is still not known whether plants that use related technologies continue to rely upon the unique skills, specialist suppliers and local knowledge that were developed within the agglomeration, and whether these external economies act as a form of related externality. Within this context, the aim herein is to examine whether the mechanisms underlying Marshallian agglomeration economies continue to operate within a declining industrial agglomeration, especially amongst the surviving plants that use related technologies.

To achieve this aim, this article uses multivariate econometric analysis to examine the original agglomeration that many regard as the origin of MARSHALL's (1890) agglomeration theory: the metals industry in Sheffield and the surrounding South Yorkshire region in the United Kingdom (KRUGMAN, 1991; FUJITA *et al.*, 1999; HARRISON, 1992; BECATTINI, 2006). The Sheffield metals industry played a unique role in the development of agglomeration theory because it was the only place about which MARSHALL (1890) argued that all three of his trinity of agglomeration economies existed during the nineteenth and twentieth centuries. The empirical results in this article illustrate that the mechanisms underlying Marshall's agglomeration economies continue to be a feature in the surviving metals industry in the city-region, but have evolved to become more prevalent amongst plants that specialize in related metals technology. It is found that plants that use related metals technology are more likely to experience each of Marshall's trinity of agglomeration economies, such as a local pool of skilled labour, local supplier linkages and local knowledge spillovers, than those plants operating in different technological environments. This article contributes to the regional development literature and evolutionary framework by being one of the first studies to examine the relationship between technological relatedness and Marshallian agglomeration economies within the context of a declining industrial agglomeration during the later stages of the industry life cycle (NEFFKE *et al.*, 2011a). Specifically, it shows how Marshallian agglomeration economies have evolved from industry-specific localization economies to become 'related externalities' that primarily occur amongst plants that specialize in related metals technology. By doing so, it also sheds light on how the original industrial agglomeration that Marshall studied has evolved over time to become a cluster of plants specializing in technologically related niches (PROPRIS and LAZZERETTI, 2009).

The article is structured as follows. Following this Introduction, the second section outlines the theoretical relationship between technological relatedness and each of MARSHALL's (1890) trinity of agglomeration economies. The third section discusses the historical context of the Sheffield metals industry and the methodological approach of this study, which uses multivariate regression models to analyse data from manufacturing plants in the city-region. Next, the fourth section presents the results from the multivariate regression models. Finally, the fifth section draws together the conclusions from the research.

THEORETICAL BACKGROUND

Within the theoretical literature the concept of technological relatedness plays a key role in explaining how firms adapt their technological routines over time (Bryce and Winter, 2009). Early research by Schumpeter (1942) and Penrose (1959) emphasizes that firm growth is driven by a continuous process of related diversification. However, when searching for new technologies and markets, firms are often confronted by a number of uncertainties (Nelson and Winter, 1982). To reduce these uncertainties, many firms choose to build upon their technological core competencies by specializing in technologically related industries, rather than risk entering unrelated industries. According to Timmermans and Boschma (2011, p. 2) this technological relatedness occurs when

> economic entities like firms or industries have a higher scope for interactive learning when there is some degree but not too much cognitive proximity between firms and industries.

For instance, Penrose (1959) argues that when firms pursue a product differentiation strategy they initially stay close to their existing technological capabilities by specializing in related technological fields in closely related industries. Breschi *et al.* (2003) found that technological relatedness is an important driver of a firm's technological diversification strategy, and that many firms develop specializations by extending their research and development activities into technologically related fields.

At the regional scale, technological relatedness occurs when firms within a region operate within technologically related industries that have overlapping knowledge bases (Boschma and Frenken, 2011a), rather than a region that is dominated by a single industry (Marshall, 1890) or a region that contains a diverse mixture of unrelated industries (Jacobs, 1969). As argued by Boschma and Frenken (2011a), firms from technologically related industries within a region are likely to persist over time because there are more opportunities for them to expand and diversify into closely related industries in order to survive (Neffke *et al.*, 2011b; Martin and Sunley, 2011). In particular, within the Evolutionary Economic Geography literature a growing number of studies have begun to examine the importance of technological relatedness to industrial clustering (Boschma and Weterings, 2007), spinoff dynamics (Heebels and Boschma, 2011), labour mobility (Boschma *et al.*, 2009), plant survival (Neffke *et al.*, 2012), and regional growth (Frenken *et al.*, 2007).

However, research is only just beginning to explore the relationship between technological relatedness and Marshallian agglomeration economies (Neffke *et al.*, 2012). Although Marshallian agglomeration economies are often regarded as industry-specific localization economies (Krugman, 1991), research by Neffke *et al.* (2011a) argues that they can also influence firms from technologically related industries that use compatible skills, related technologies, complementary assets and similar technological know-how. In particular, rather than industrial specialization increasing the survival chances of plants, Neffke (2008) found that the local presence of technologically related industries has a significant positive effect on plant survival. Given the importance of technological relatedness to regional evolution, there remains a gap within the regional development literature with respect to the relationship between technological relatedness and the evolution of agglomerations (Boschma and Frenken, 2011a). In particular, comparatively little is known about the role that technological relatedness plays in the context of a declining industrial agglomeration during the later stages of the industry life cycle, when firms face greater pressure to adapt and diversify into related technologies in order to survive (Sadler, 2004). In light of this, the article now outlines the relationship between technological relatedness and each of Marshall's trinity of agglomeration economies: a local pool of skilled labour, local supply chain linkages and local knowledge spillovers.

A local pool of skilled labour

Since Marshall's (1890) agglomeration theory, it is well established within the regional development literature that a local pool of skilled labour is an important driver of firm performance and regional development (Saxenian, 1994). However, comparatively less attention has been given to the evolution of skills within an industrial agglomeration and the implications this has for the nature of Marshallian agglomeration economies (Boschma *et al.*, 2009; Neffke *et al.*, 2011a). As an industry evolves, there is often a gradual transformation from blue collar skills to white collar skills and a research shift from the skills that focus on creating product innovations to those that emphasize production innovations and incremental continuous improvements (Utterback and Abernathy, 1975; Hayes and Wheelwright, 1979; Klepper, 1997). Furthermore, over time the types of skills required by firms also changes, with more attention given to how skilled employees can improve production productivity, reduce costs, develop production innovations, enhance production technology and re-engineer products to help firms diversify into related industries (Audretsch and Feldman, 1996; Klepper, 1996). Therefore, within the context of a declining agglomeration there is often a high demand for employees with specialist skills in production-related technologies, ranging from analytical, scientific and problem-solving skills to engineering, production and managerial skills from technologically related industries (Grabher, 1993; Sadler, 2004; Menzel and Fornahl, 2010).

In response to the decline of an industrial agglomeration, many firms adopt a related diversification strategy that focuses on adapting their organizational routines, skills, technology, and knowledge to develop related technologies and enter related industries (BRESCHI *et al.*, 2003). An early study by RUMELT (1977) argues that employee skills are the key to the success of related diversification strategies, especially when firms extend their *core skills* into related technological fields. In particular, the skills developed in one industry can often be applied to related industries when there is a skills overlap in common scientific and engineering principles (that is, so-called *related skills*) (NEFFKE *et al.*, 2012; BOSCHMA *et al.*, 2009). In other words, employees with related skills will be able to adapt the scientific principles, organizational routines and core skills that developed within the agglomeration with the skills used within related technological fields. For example, research by NEFFKE and HENNING (2009) has found that firms are more likely to diversify into related industries that have similarities with their core skills, technologies and production processes, rather than enter unrelated industries where there is no skills overlap. As there are more opportunities for employees to interact and learn from related technologies within agglomerations, it is likely that these related skills will be more prevalent within agglomerations where there is a common technological skill base that can be applied to different related industries. Furthermore, due to the weaker presence of industry-specific skills within a declining agglomeration and the diversification of existing firms into related technological fields, it is likely that related skills will become more prevalent over time.

During the later stages of the industry life cycle, firms can also experience greater pressure to improve production productivity, lower costs, lower product prices and increase operational performance, especially within the context of declining agglomerations that face international competition from emerging low-cost economies (KLEPPER, 1996; SADLER, 2004). To achieve these goals, firms will often hire employees with skills in related production technologies from technologically related industries that can be applied to help raise production productivity and increase operational performance (BOSCHMA *et al.*, 2009). Hiring skilled employees from technologically related industries enables firms to learn from their prior experience, accumulated knowledge and related skills, which can then be applied to upgrading the production productivity of the firms within the agglomeration (TIMMERMANS and BOSCHMA, 2011). BOSCHMA *et al.* (2009) argue that the impact of labour mobility and skills on plant performance can vary depending upon the extent to which the types of skills match the existing skills base within a plant (TIMMERMANS and BOSCHMA, 2011). For instance, research by BOSCHMA *et al.* (2009) into labour mobility in Sweden identified that recruiting employees with skills that are related to the plant's existing knowledge base increases the plant's productivity growth, whereas hiring new employees with skills that are similar to the plant's existing skills base has a negative impact. Overall, it appears that within the context of a declining industrial agglomeration the plants that specialize in related technologies will be more dependent upon a local pool of skilled labour.

Local supply chain linkages

MARSHALL (1890) also highlighted the role that local supplier linkages, local customer linkages, ancillary trades and supporting services play within an industrial agglomeration, which indicates that he understood the importance of technologically related industries to the development of firms and agglomerations. Whilst Marshall's agglomeration theory emphasizes that firms can receive increasing returns from supply chain linkages to a local supplier market, comparatively little is known about how these specialist suppliers, customers and their related technologies co-evolve within the agglomeration. Recent research suggests that these local related industries often co-evolve as a result of firms within the agglomeration diversifying and branching out into related technologies (FRENKEN and BOSCHMA, 2007; TER WAL and BOSCHMA, 2011). For example, corporate diversification and strategic reorientation towards technologically related industries was observed during the decline of the Ruhr Valley steel industry, where many leading metal producers simultaneously reduced their metal steel production activities and diversified into technologically related niche industries such as electronics, mechanical engineering and environmental technology (GRABHER, 1993). Similar research by SADLER (2004) into the evolution of the steel cluster in the North East of England also found a high degree of diversity within the local supply chain, with many engineering firms evolving to become specialized process service providers, general engineering firms or bespoke design-dependent firms in related industries.

Moreover, BOSCHMA and FRENKEN (2006) argue that technological relatedness is an important driver of the birth and evolution of new technologies, new product innovations, and even entirely new industries and clusters (BOSCHMA and FRENKEN, 2011b). This process by which new industries evolve from the interactions between technologically related industries is referred to as 'regional branching', and is regarded by many as an important determinant of routine hybridization and regional evolution (FRENKEN and BOSCHMA, 2007). A number of studies have identified that technological relatedness fosters the branching of new knowledge, routines, products, innovations, industries and clusters, which often evolve from the interactions between existing and related industries within a city-region (BOSCHMA and FRENKEN, 2011a). Over time, this regional branching process helps to ensure the continued survival of firms within the agglomeration by fostering the evolution of hybrid organizational routines, product innovations, new technological trajectories and new development paths for the city-region

(Martin and Sunley, 2006). Notably, Boschma and Ledder (2009) emphasize that once a critical mass of founding firms, spinoffs, new entrants and related technological industries agglomerate within a city-region, their growing demand will lead to the development of agglomeration externalities, such as local supplier linkages, local customer linkages, local capital investment suppliers and local service suppliers.

Local knowledge spillovers

Research indicates that the degree of technological relatedness between firms within a region is an important determinant of the extent of local knowledge spillover, as Boschma and Frenken (2011b, p. 66) argue: 'technological relatedness is expected to affect, first and foremost, the extent to which knowledge spillovers occur within a region'. Frenken *et al.* (2007) suggest that when a high degree of related variety exists within a region among different but complementary related industries, there will be greater opportunities for local knowledge spillovers. Shedding light on the debate about regional specialization versus variety debate, Boschma and Frenken (2011b) also argue that local knowledge spillovers are less likely to occur within regions with a large diversity of unrelated industries (that is, Jacobs externalities) and regions that contain an industrial agglomeration of firms from a single industry (that is, Marshallian externalities) because firms often learn more from technologically related firms in related industries that have some but not too much cognitive proximity (that is, related externalities). In other words, firms with different but related technological capabilities, such as overlapping assets, similar tacit knowledge and complementary organizational routines, are more likely to share local knowledge spillovers, in comparison with firms that use unrelated technologies. Therefore, one would expect to find that local knowledge spillovers are more prevalent amongst firms that use related technologies within a city-region. In particular, the spillover of knowledge among related firms enables the cross-fertilization of new knowledge, which, when combined with existing pools of knowledge, leads to the creation of further local knowledge spillovers in an ongoing process of knowledge creation, recombination and adaptation (Schumpeter, 1942).

Research hypotheses

Within the regional development literature it is well established that Marshall's (1890) agglomeration economies help to generate increasing returns when firms from the same industry agglomerate together in close geographical proximity (Krugman, 1991; Porter, 1998). Using an evolutionary perspective, a number of recent studies have begun to explore the relationship between technological relatedness and the evolution of firms, industries, agglomerations and regions (Boschma and Frenken, 2006, 2011a). Although Marshallian agglomeration economies are regarded by many as industry-specific localization economies, comparatively few studies have explored whether firms that use related technology also depend upon a local pool of skilled labour, local supplier linkages, local customer linkage, local capital investment suppliers, local service suppliers and local knowledge spillovers. Furthermore, whilst prior research has identified that technological relatedness plays a key role in the birth and growth of new industries and agglomerations, few studies have examined its effect within the context of a declining agglomeration during the later stages of the industry life cycle (Neffke *et al.*, 2011a). In particular, during the later stages of the industry life cycle, the plants within a declining agglomeration face greater pressure to adapt their organizational routines and migrate into related technologies in order to survive (Martin and Sunley, 2011). Building upon recent research within Evolutionary Economic Geography, it is argued here that Marshallian agglomeration economies continue to affect firms that use technology that is related to the technological know-how developed within the agglomeration, especially within the context of a declining industrial agglomeration. Within this context, it is proposed here that when firms use related technology, they continue to rely upon the unique skills, specialist suppliers and technological know-how that were developed within the agglomeration. This leads to the following research hypotheses:

Hypothesis 1: Plants that use related technology continue to rely on a local pool of skilled labour.

Hypothesis 2: Plants that use related technology continue to maintain local supplier linkages.

Hypothesis 3: Plants that use related technology continue to maintain local customer linkages.

Hypothesis 4: Plants that use related technology continue to source from local capital investment suppliers.

Hypothesis 5: Plants that use related technology continue to source from local service suppliers.

Hypothesis 6: Plants that use related technology continue to receive local knowledge spillovers.

RESEARCH METHODOLOGY

Historical context

The metals cluster in the city of Sheffield and the surrounding South Yorkshire region in the UK played a key role in the emergence of Marshall's (1890) agglomeration theory. It is widely argued that Marshall's agglomeration theory originated from the face-to-face interviews he undertook personally with managers from manufacturing plants in the Sheffield metals industry. Over eighty economists, geographers and economic historians agree that the Sheffield metals industry was the location wherein Marshall identified the trinity of agglomeration economies (KRUGMAN, 1991; FUJITA *et al.*, 1999; DUNNING, 2000; HARRISON, 1992; SIMMIE, 1997; BECATTINI, 2006). As shown clearly in Table 1, MARSHALL (1890) made direct references to the metals industry in Sheffield for each of his trinity of agglomeration economies.

Today, the South Yorkshire city-region has a population of 1.4 million people and at its centre is the city of Sheffield, the fifth largest city in England (Fig. 2). As PROPRIS and LAZZERETTI (2007) argue, the evolution of a Marshallian industrial district in a particular place and time is often historically driven rather than the outcome of a random event. From a historical perspective, this city-region has a long history of innovation and production in the metals industry (TWEEDALE, 1995; HEY, 2005). Although iron smelting in the region dates back to before Roman times, the metals industry grew steadily from the thirteenth century, with an important marker being the formation of the Company of Cutlers in 1624 (HEY, 2005). Further key events in the region's history were the locally developed innovation of crucible steel by Benjamin Huntsman in 1740 and the innovation of Sheffield plate metal by Thomas Boulsover in 1742, which strengthened the embryonic agglomeration. Interestingly, Huntsman was skilled in a number of related metal industries, such as the manufacturing of clocks, locks, tools and steel, which many argue contributed to the invention of his crucible steel innovation (TWEEDALE, 1995). Like the Birmingham jewellery Marshallian industrial district (PROPRIS and LAZZERETTI, 2007), by the mid-nineteenth century the Sheffield metals industry contained a diverse mixture of light and heavy trades in related metals industries. Throughout the nineteenth century industries that were technologically related to the metals industry continued to evolve within the city-region, often specializing in the production of small batches of metal products, which were classed as 'light trades' such as cutlery, tools, blades, razors, saws, scythes, metal boxes, anvils and files. This high degree of technological relatedness was noted in an early study of Sheffield in 1824, which identified over sixty different types of metal products being manufactured in the city-region (TWEEDALE, 1995). Using an evolutionary perspective, TWEEDALE (1995) emphasizes that 'one of the most striking of Sheffield's characteristics was the multitude of support trades, orbiting around the steel nucleus' (p. 42). However, it was Henry Bessemer's famous invention of the Bessemer converter production innovation in Sheffield during 1856 that enabled the first mass production of steel and led to the evolution of what were termed the 'heavy trades' within Sheffield's metal industry. At one point in the last half of the nineteenth century the metals agglomeration in the city-region had monopolized the metals industry and was producing 90% of the total metal steel output of Britain, half of the total metal steel output of the rest of Europe and North America, and half of the world's total metal steel output (TWEEDALE, 1995). Bessemer's was not the last local innovation: manganese steel was invented by Sheffield manufacturer Robert Hadfield in 1882, followed by one of the most famous inventions in the metals industry, namely Harry Brearley's invention of stainless steel within the city-region in 1912. Crucially, this helped to reinvent the city-region as a centre of innovation and production in stainless steels and specialist metals, which provided the agglomeration with an extended life cycle and the region with a new development path (MARTIN and SUNLEY, 2011). In particular, the invention of stainless steel represents a form of 'regional branching' in which this radical innovation and new industry evolved from the integration of knowledge, organizational routines and technology from technologically related industries within the city-region (FRENKEN and BOSCHMA, 2007). Just like the Birmingham jewellery industrial district (PROPRIS and LAZZERETTI, 2007), at the start of the twentieth century the Sheffield metals industry contained all the features of an archetypal Marshallian industrial district.

Table 1. Marshall's agglomeration economies and the Sheffield metals industry

Agglomeration economies	Marshall's analysis of the Sheffield metals industry
(i) A local pool of skilled labour	'The leadership in a special industry, which a district derives from an industrial atmosphere, such as that of Sheffield or Solingen, has shown more vitality than might have seemed probable in view of the incessant changes of technique. The explanation is perhaps to be found in the fact that an established centre of specialized skill ….' (MARSHALL, 1919, p. 190)
(ii) Local supplier linkages	'Or there may be a movement towards intermediate plans, similar to those which are largely followed in the Sheffield trades. Many cutlery firms for instance put out grinding and other parts of their work, at piece-work prices, to working men who rent the steam power which they require, either from the firm from whom they take their contract or from someone else: these workmen sometimes employing others to help them, sometimes working alone.' (MARSHALL, 1890, p. 296)
(iii) Local knowledge spillovers	'Sheffield and Solingen have acquired industrial "atmospheres" of their own; which yield gratis to the manufacturers of cutlery great advantages, that are not easily to be had elsewhere: and an atmosphere cannot be moved.' (MARSHALL, 1919, p. 176)

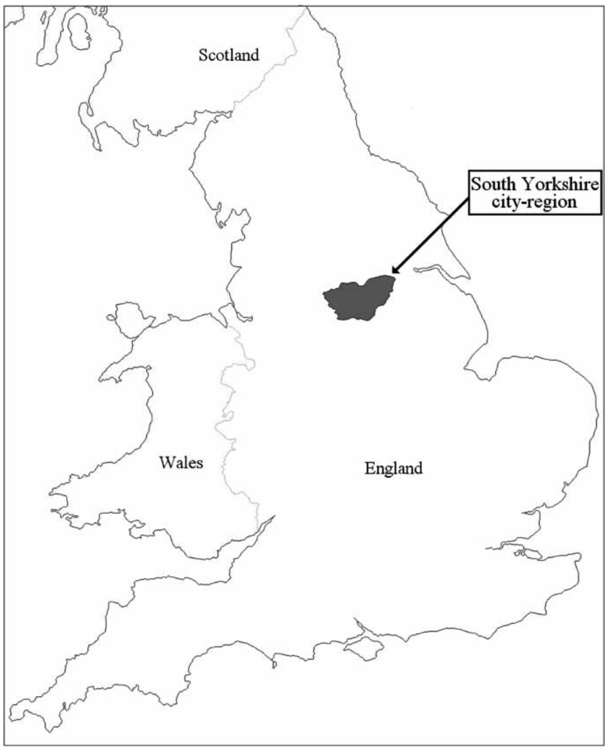

Fig. 2. The South Yorkshire city-region

Once at the centre of the Industrial Revolution, from the 1970s onwards employment in the metal industry declined. Using the narrow definition of the metal industry from the Standard Industrial Classification (SIC) statistics, employment fell from 42 000 in 1981 to 20 000 in 1991, to 17 000 in 2001 and to 12 000 in 2008 (NATIONAL On-line MANPOWER INFORMATION SYSTEM (NOMIS), 2008). Like many other industrial districts, the fall in employment in the metals industry and the closure of metal plants arose from a number of factors, including the evolution of the industry life cycle, production overcapacity, technological changes, production automation, government regulations, a failure to adapt to low-cost international competitors, an unwillingness to adopt new management practices, and the simultaneous decline of many customer markets within the UK (TWEEDALE, 1995; SADLER, 2004; PROPRIS and LAZZERETTI, 2009). Taken together, the fall in labour input and employment, the closure of large manufacturing plants and the decline of the metals agglomeration resulted in the South Yorkshire city-region becoming one of the poorest (Objective 1) regions in the European Union in the first decade of the twenty-first century (EUROPEAN COMMISSION, 2005).

In view of this particular industrial history, it is not surprising that the development path of the city-region became locked into the life cycle of the metals industry, so that when MARSHALL (1890) conducted his research in the city-region, the local metals agglomeration was expanding rapidly during the early stages of the industry life cycle. In contrast, the present analysis is based on data drawn from the later stages of the industry life cycle. By 2008, within the city of Sheffield, there were some 12 000 employees remaining in the local metals industry (as defined by the SIC). This was made up of 4000 employees in basic metals involved in the manufacture of stainless steel, engineering steel, metal casting and metal rolling wire products. The proportion was slightly higher than the national average, with a location quotient (LQ) of 1.3 (NOMIS, 2008; OFFICE FOR NATIONAL STATISTICS (ONS), 2008a). However, 8000 employees continued to work in the production of fabricated metal products, which was much higher than the national average (LQ = 2.5). These employees were working in metal forging, machine tools and domestic tools, with a very small element still involved in metal cutlery. There were almost 500 plants involved in fabricated metals production (with a mean size of twenty-four employees) compared with just fewer than sixty plants that continue to manufacture basic metals (with a mean size of seventy-two employees) (ONS, 2008b). No less than 85% of the fabricated metals plants had twenty-four employees or fewer. Their 2450 employees represented less than one-third of employment in this sub-industry. Despite the plethora of small plants, the local metals industry continues to be dominated by employment in medium and large plants. In South Yorkshire itself, just over half the employment in the local metals industry by 2008 was in medium and large plants; whilst in the basic metals sub-industry the proportion was 87%. Furthermore, LQ analysis reveals that the city-region contains a significant overrepresentation of medium and large manufacturing plants in comparison with the national average (ONS, 2008b).[1]

Data collection

This study adopts a similar approach to that of MARSHALL (1890) by collecting detailed data from a large cross-section of medium and large manufacturing plants in the manufacturing sector in the city-region,[2] and like Marshall close attention is paid to the larger manufacturing plants. Following recognized definitions by the SIC and the EUROPEAN COMMISSION (2005), a population of 367 medium and large manufacturing plants was identified as meeting the selection criteria from secondary data sources and local fieldwork in the city-region (COMPANIES HOUSE EXECUTIVE AGENCY, 2005). After a semi-structured interview schedule had been pilot-tested, face-to-face interviews were conducted with managers from ninety manufacturing plants. However, eleven plants were identified as not meeting the selection criteria and were subsequently removed, resulting in a final sample of seventy-nine manufacturing plants.[3] With a response rate of 22%, this sample represents one-quarter of the region's manufacturing employment.

Empirical analysis

A multivariate approach was used to determine whether the mechanisms underlying MARSHALL's (1890) agglomeration economies were more prevalent amongst plants from the local metals industry, especially amongst those that use related metals technology. To explore the latter theme the metals industry was divided into two categories. The first category included those plants using closely related metals technology; the second category encompassed those plants using unrelated metals technology. In the multivariate regression models, each dependent variable measures a different mechanism that underlies Marshall's agglomeration economies, whilst the independent variables include an explanatory variable related to the research hypothesis (that is, metals industry, related metals technology, unrelated metals technology), which is then followed by a series of control variables (see Table A2 in Appendix A). Multicollinearity[4] and assumption tests were conducted throughout the econometric analysis, with particular attention given to non-normality and heteroskedasticity, which can cause biased, inconsistent and inefficient estimations (SMITH and BRAME, 2003). The models remain robust, with reasonable levels of model fit. Admittedly, some of the results from the models have comparatively low levels of model fit, but they are in accordance with similar models that examine declining industrial clusters. Overall, the models meet the multicollinearity and assumptions test criteria, but the comparatively low levels of model fit for some of the models should be taken into consideration when evaluating the conclusions from the empirical analysis.

Multivariate tobit regression models[5] are used to examine the first, second and third research hypotheses (that is, for highly skilled labour, local supplier linkages and local customer linkages), and multivariate logistic regression models[6] are applied to the fourth, fifth and sixth research hypothesis (that is, for local capital investment suppliers, local service suppliers and local knowledge spillover) (TOBIN, 1958; MADDALA, 1983). Multivariate tobit models are used when observations cluster towards end-points along an interval scale, which can violate the linearity and normality assumptions of an ordinary least squares (OLS) regression and potentially lead to biased OLS coefficient estimates (MCDONALD and MOFFITT, 1980). These tobit models use a maximum likelihood estimation method to generate a censored regression equation, and have been designed specifically to handle situations where the dependent variable has been censored, especially when the dependent variable has been censored to a range from 0% to 100% (AMENIYA, 1984). Since the 1980s, these tobit regression models have been used extensively in the regional development literature (BOSCHMA and WETERINGS, 2005) and have been frequently employed to measure the degree of local supplier linkages in a city-region (HEWITT-DUNDAS *et al.*, 2005). Based upon the econometrics literature, multivariate OLS regression models are also displayed in the results tables to measure the sensitivity of the tobit results to different estimation methods (VEALL and ZIMMERMAN, 1994). However, since the fourth, fifth and sixth research hypotheses use dichotomous dependent variables, multivariate logistic models are used instead (MADDALA, 1983). Multivariate logistic models use a maximum likelihood estimation method to estimate the likelihood of an event occurring, such as the likelihood that a manufacturing plant receives a local knowledge spillover (GREENE, 2008).

Measuring agglomeration economies

This study employs one of the most widely used measures of employee skills, which has been used successfully in a number of empirical studies in regional development (BOSCHMA *et al.*, 2009; ROBSON and BENNETT, 2000). During the interviews, respondents were asked a series of detailed questions about the characteristics of the workforce at their manufacturing plant, and were asked to use their internal payroll accounts to quantify the proportion of their on-site employees who were highly skilled. Consistent with regional, national and international research, highly skilled employees were defined as those trained to university degree level (or to the industry's own equivalent standard), such as formally qualified engineers, researchers, technologists or scientists (BOSCHMA *et al.*, 2009; EUROPEAN COMMISSION, 2005). On average, plants reported 50% of their employees (median and mean) as highly skilled, and this was especially apparent amongst plants using related metals technologies, as many managers highlighted their dependence on a local labour market of skilled employees trained in metallurgy, materials science and the engineering sciences. Although the measure of employee skills is consistent with similar measures used in regional, national and international empirical studies, like any measure it also has limitations, such as the assumption that employees reside within the region, the continued reliance upon a local skilled labour market, and the difficulty of capturing the nuances of learning by doing and on-the-job training (BOSCHMA *et al.*, 2009). Consequently, the interpretation of these results proceeds cautiously, bearing these limitations in mind.

To measure the second of MARSHALL's (1890) trinity of agglomeration economies, respondents were asked a series of detailed questions about the local supplier linkages between their plant and local suppliers in the region. Respondents were asked to quantify the percentage of the expenditure of the manufacturing plant, by value, on materials and components sourced from local suppliers in the city-region (BARKLEY and MCNAMARA, 1994). This is one of the most widely used measures of local supplier linkage in the regional development literature (HEWITT-DUNDAS *et al.*, 2005). Manufacturing plants sourced a mean of 17%, and a median of 4%, of their expenditure on materials and components from local suppliers in the city-region, a result that is similar to those of past regional studies (BRAND *et al.*, 2000; WATTS *et al.*, 2003). It is important to highlight, however, that there is a large degree of variation in the sample with respect to the propensity to source locally (SADLER, 2004). Similar to past linkage studies, many manufacturing plants sourced only a small proportion of their materials locally (BARKLEY and MCNAMARA, 1994; SADLER, 2004), with the majority of plants being more dependent on global supply chains (HUMPHREY and SCHMITZ, 2002). Despite this trend, there still exists a distinctive group of plants with substantial local supplier linkages to key local suppliers within the metals agglomeration.

As it is important to capture the degree of local supply chain linkages within the city-region, data were also collected on the extent of local customer linkages between plants and the local customer market. To measure the extent of local customer linkage, each respondent was asked to quantify the percentage of their plant's sales turnover, by value, from local customers within the city-region. In accordance with similar studies, plants were not heavily reliant upon the local customer market, with many local customer linkages being of small importance (that is, mean = 8%, standard deviation (SD) = 14%) (GRABHER, 1993). As expected, many of the plants were part of global supply chains and were dependent on international export markets for their growth, especially in the rest of Europe, North America and, increasingly, Asia.

It was also measured whether plants sourced from any local capital investment suppliers that were located within the city-region, many of which had co-evolved with the development of the local metals agglomeration (TER WAL and BOSCHMA, 2011). Overall, 46% of plants sourced from capital investment suppliers within the city-region. These suppliers provided a range of products, including machine tools, manufacturing dies, machinery equipment, production technology, process machinery and industrial machines.

To gain a full picture of the extent of linkage between local manufacturing plants and other firms within the region, data on whether plants sourced from local service suppliers within the city-region were also captured. These local service suppliers provided a wide range of different services, including technology, maintenance, accounting and financial services. In line with prior studies, a greater proportion of plants, some 71%, sourced services locally within the city-region (HEWITT-DUNDAS *et al.*, 2005).

In response to KRUGMAN's (1991) declaration that knowledge spillovers cannot be measured because they leave no paper trail, a number of studies have used patent and citation data as proxy measures of local knowledge spillovers (JAFFE *et al.*, 1993). However, reliance upon patent statistics does introduce a substantial bias towards research and development-intensive firms at the start of the industry life cycle, with comparatively little, if any, research being conducted on local knowledge spillovers in the context of a declining agglomeration towards the end of the life cycle (AUDRETSCH and FELDMAN, 1996). To overcome these limitations, a large number of empirical studies have found that it is possible to measure directly the spillover of knowledge between firms through the use of face-to-face interviews (CRONE and ROPER, 2001). During the interviews, respondents were asked whether their plant had received knowledge from local customers, local suppliers, other local manufacturing plants, local capital investment suppliers or local service suppliers in the region. To ensure measurement validity, a number of steps were taken to verify these local knowledge spillovers. First, during the interviews, a knowledge spillover was defined as knowledge valued at a minimum of £1000 or the equivalent to five days of inter-firm knowledge transfer (POTTER and WATTS, 2010). Second, to improve measurement validity, each interviewee was presented with a list of the different types of local knowledge spillover they could receive, which was based upon prior classifications of local knowledge spillover by CRONE and ROPER (2001), DUNNING (2000), and POTTER *et al.* (2003). Using this measure of local knowledge spillover, 32% of the manufacturing plants had received a local knowledge spillover from within the region in the past three years. In addition, further data were also collected on whether each plant had provided knowledge locally within the region (yes = 40%, no = 60%), and this additional measure of local knowledge spillover was used in the analysis to examine measurement validity.

Explanatory variables

Although one of the most frequently used methods of classifying industries is the Standard Industrial Classification (SIC), classifying manufacturing plants into different industries is notoriously difficult (AUDRETSCH and FELDMAN, 1996). For example, the SIC definition of the metals industry is very narrow, encompassing mainly producers of raw metals, and does not reflect the diversity of metal manufacturers in the city-region. To rectify this limitation, the present approach builds upon similar studies that classify technological relatedness according to underlying scientific and engineering principles (BRESCHI *et al.*, 2003). The classification method employed is one that is widely used in the engineering sciences (CALLISTER, 2007). Engineers frequently classify materials according to their metallurgical content, that is, whether it is a ferrous or a non-ferrous metal (PICKERING, 1978). Using this engineering classification, a manufacturing plant is classified as being in the metals industry if the majority of its material inputs or final products contain metal (either ferrous or non-ferrous metal) (CALLISTER, 2007). During the face-to-face interviews, detailed data were collected on the types of material inputs the manufacturing plants used in their production processes and the types of final products they produce. Using these detailed data, together with the engineering classification, it was discovered that 62% of the manufacturing plants were operating in the metals industry. Within the empirical analysis, the authors began by comparing plants from the metals industry with plants from unrelated industries in the manufacturing sector of the region to establish whether metal plants continued to be more reliant on Marshallian agglomeration economies, which would indicate the presence of industry-specific localization economies.

Attention now turns to the primary focus of this article: the relationship between technological relatedness and the degree of Marshallian agglomeration economies experienced by plants within the city-region. Within the literature a number of notable authors, including BRYCE and WINTER (2009), argue that technological relatedness cannot be accurately measured using SIC statistics. Therefore, as recommended by BRESCHI *et al.* (2003), this article turns to the classification method used within the engineering sciences, which separates different types of metal products into ferrous and non-ferrous metals. Within the engineering sciences, ferrous metals are defined as those that primarily contain iron, such as pure iron, metal alloys and especially metal steel (which is a metal alloy of iron and carbon) (PICKERING, 1978). Uniquely, the metal plants within Sheffield played a major role in the development of ferrous metal technology, such as the invention of stainless steel and various specialist steels and metal alloys (TWEEDALE, 1995). In particular, within the engineering, materials science and metallurgy literatures, the Sheffield metals industry is renowned as the location where ferrous metal technology was invented (CALLISTER, 2007). In other words, the metals agglomeration within the city-region was not just an industrial agglomeration of plants from the same metals industry, it was also a technological agglomeration that specialized in the invention and development of ferrous metals technology. Within this study it was found that 24% of plants continue to use ferrous metal technology to produce and manufacture products that contain ferrous metal. However, although these plants continue to use the ferrous metals technology that was developed within local agglomeration, over time they have adapted this technology with new innovations, technology, technical know-how and scientific developments from related technological fields (for example, tool steel, high-speed steel, high-tensile steel, high-carbon steel). In particular, these metal manufacturers have diversified into related technological niches and they now produce a wider range of steel grades, specialist steels, metal alloys and specialist metal products. Therefore, it is more appropriate to refer to these hybrid metal plants as using related metal technology, as they have all adapted the ferrous metals technology that was developed within the city-region with the technology from related technological fields (BRESCHI *et al.*, 2003). Managers indicated that this migration into related metal technology was primarily driven by the decline and restructuring of the local metals industry during the later stages of the industry life cycle, which forced many plants to adapt in order to survive (MARTIN and SUNLEY, 2011). In addition, many of the managers commented that they had adapted by following a product differentiation strategy that involved specializing in higher growth-related technologies (for example, super alloys, tool steel, high-strength steels, spring steel, aerospace steel, high-carbon steel, corrosion-resistant steel), often to become niche providers of specialist high-value-critical products to the aerospace, automotive, electronics, oil and gas, and defence industries. Furthermore, this diversification into related metal technology was also actively encouraged by policy-makers at the European Commission Objective 1 Programme Directorate, who targeted a large share of their £2.4 billion investments at metal plants that were developing related metal technology and moving strategically into high-growth technologically related industries.

Finally, also examined were those plants that use non-ferrous metal technology to produce products that do not contain iron, which include metals such as copper, tin, aluminium, zinc and brass, as well as particular types of precious metals, such as platinum, silver and gold (CALLISTER, 2007). Crucially, from a historical perspective, these non-ferrous metal technologies were primarily developed outside of the city-region, and therefore these plants are unlikely to rely upon the metal technology that was developed within the local metals agglomeration. Upon close inspection of the data, it is clear that over time these plants have also diversified, but they continue to operate in unrelated technological fields to the technology that was developed locally within the metals agglomeration. Therefore, those metal plants that primarily manufacture non-ferrous metal products are classified as relying upon unrelated metals technology because this technology was primarily developed outside of the city-region. It is found that 38% of plants within this study are manufacturers of non-ferrous metal products that use unrelated metals technology. Using a unique classification method from the engineering sciences, the measures of related metals technology and unrelated metals technology capture the technological relatedness of plants in the sense that they clearly identify whether plants specialize in related technological fields but continue to use the local technology that was invented within the local metals agglomeration (that is, related metals technology) or whether they currently use unrelated technologies developed outside the region (that is, unrelated metals technology).

EMPIRICAL RESULTS

Local pool of skilled labour

Table 2 presents the results from the multivariate tobit regression models, in which the rows refer to the explanatory variable and control variables and the cells are the coefficients, with the level of statistical significance. As expected, manufacturing plants in the metals industry are more likely to employ highly skilled labour, which is in keeping with the evolution and history of the city-region (TWEEDALE, 1995; HEY, 2005). Not only does this positive relationship remain statistically significant at the 95% level ($p < 0.05$), but also it does so whilst controlling for the influence of a wide variety of different control variables. More importantly, the results in Table 2 identify that plants using related metals technology ($p < 0.01$), rather than unrelated metals technology (p = n.s.), tend to have a more highly skilled workforce.[7] Overall, these multivariate results clearly support the first research hypothesis, and illustrate that metal plants that specialize in related technological fields continue to rely upon a local pool of skilled labour. During the interviews, managers highlighted the importance of related skills to their plant's survival, especially their highly skilled employees that can combine, integrate, reconfigure and adapt technological know-how that spans related industries (BRESCHI *et al.*, 2003).

Local supplier linkages

Turning to the multivariate results for local supplier linkages in Table 3, the tobit estimation results indicate that manufacturing plants from the metals industry source a larger percentage of their materials from local suppliers within the city-region ($p < 0.01$). For the results concerning technological relatedness, it appears that there is an important distinction between plants that use related metals technology ($p < 0.01$), which are more dependent on local supplier linkages, and those that use unrelated metals technology (p = n.s.).[8] Many of the managers from plants that use related metals technology commented that although local suppliers were often price uncompetitive, they continued to source from the local supply base in order to access these suppliers' technological expertise, engineering advice, technical support and unique metallurgical know-how. Over time, as plants had evolved to become specialists in related technological fields, they had become more reliant upon their local suppliers' technological know-how, which they use to help solve technical problems during the production of specialist niche products for related industries (CRONE and ROPER, 2001). Therefore, although the degree of local sourcing remains comparatively low during the later stages of the industry life cycle, it appears as though plants that use related metals technology continue to maintain local supplier linkages within the city-region in order to gain access to their suppliers' technological knowledge (GRABHER, 1993; SADLER, 2004).

Local customer linkage

Going beyond MARSHALL's (1890) original agglomeration economies, it was also examined whether manufacturing plants in the metals industry maintain greater local customer linkages in the city-region. Here the same multivariate tobit models are used as before, but the dependent variable is replaced with a measure of the percentage of sales turnover from local customers in the city-region. The results shown in Table 4 identify

Table 2. Multivariate tobit regression models for the estimation of highly skilled labour

	Model 1 (tobit)	Model 2 (OLS)	Model 3 (tobit)	Model 4 (OLS)	Model 5 (tobit)	Model 6 (tobit)
Explanatory variables						
Metals industry	10.81**	11.25**	–	–	–	–
Related metals technology	–	–	19.34***	18.57***	–	–
Unrelated metals technology	–	–	–	–	−3.70	−2.62
Control variables						
Plant size	−3.98	−3.59	−5.15	−4.67	−3.66	−3.20
Plant history	−3.80	−3.64	−3.97*	−3.83	−4.03*	−3.86
Local ownership	6.80	7.09	3.81	4.04	3.67	4.09
Original equipment manufacturing (OEM) plant	−8.93	−8.89	−7.56	−7.61	−9.13	−9.21
Engineer-to-order (ETO)	16.95**	16.47**	14.56**	14.27*	18.37**	17.84**
Product innovation	8.72	7.47	11.48*	9.97	7.91	6.41
(Constant)	66.62***	64.79**	74.89***	73.32***	75.57***	73.31***
R^2	0.18	0.18	0.21	0.22	0.15	0.15
R^2 (adjusted)	0.10	0.10	0.12	0.14	0.05	0.07
n	79	79	79	79	79	79

Notes: *Statistically significant at the 90% level; **statistically significant at the 95% level; and ***statistically significant at the 99% level (one-tailed tests).

OLS, ordinary least squares.

Table 3. Multivariate tobit regression models for the estimation of local supplier linkage

	Model 1 (tobit)	Model 2 (OLS)	Model 3 (tobit)	Model 4 (OLS)	Model 5 (tobit)	Model 6 (OLS)
Explanatory variables						
Metals industry	27.60***	15.01***	–	–	–	–
Related metals technology	–	–	38.76***	29.94***	–	–
Unrelated metals technology	–	–	–	–	−5.00	−7.24
Control variables						
Plant size	−7.59	−5.10	−9.53**	−6.98**	−6.34	−4.73
Plant history	−0.42	−0.50	−1.00	−0.75	−1.02	−0.86
Local ownership	−7.71	−7.14	−14.63**	−11.41**	−14.34*	−12.06*
Original equipment manufacturing (OEM) plant	−10.75	−7.88	−7.17	−5.69	−11.18	−8.12
Engineer-to-order (ETO)	2.73	2.33	−1.83	−1.65	6.58	3.93
Product innovation	−3.55	−1.71	2.58	2.69	−5.72	−2.78
(Constant)	42.59	43.51*	62.16**	55.41***	61.38*	57.49**
R^2	0.16	0.15	0.32	0.31	0.09	0.10
R^2 (adjusted)	0.06	0.07	0.25	0.24	0.00	0.01
n	79	79	79	79	79	79

Notes: *Statistically significant at the 90% level; **statistically significant at the 95% level; and ***statistically significant at the 99% level (one-tailed tests).

OLS, ordinary least squares.

Table 4. Multivariate tobit regression models for the estimation of local customer linkage

	Model 1 (tobit)	Model 2 (OLS)	Model 3 (tobit)	Model 4 (OLS)	Model 5 (tobit)	Model 6 (OLS)
Explanatory variables						
Metals industry	−0.82	−2.08	–	–	–	–
Related metals technology	–	–	4.07	0.34	–	–
Unrelated metals technology	–	–	–	–	−3.92	−2.25
Control variables						
Plant size	−0.45	−0.09	−0.83	−0.22	−0.60	−0.28
Plant history	−1.12	−0.88	−1.12	−0.85	−1.20	−0.88
Local ownership	11.81***	7.57**	11.95***	7.99**	11.13***	7.44**
Original equipment manufacturing (OEM) plant	−0.02	−0.06	0.44	0.06	0.21	0.15
Engineer-to-order (ETO)	0.98	1.75	−0.04	1.40	0.44	1.32
Product innovation	−5.95	−4.86	−5.06	−4.55	−5.56	−4.42
(Constant)	7.54	10.33	7.32	9.12	9.58	10.65
R^2	0.12	0.13	0.11	0.13	0.13	0.14
R^2 (adjusted)	0.02	0.05	0.01	0.04	0.03	0.05
n	79	79	79	79	79	79

Notes: *Statistically significant at the 90% level; **statistically significant at the 95% level; and ***statistically significant at the 99% level (one-tailed tests).

OLS, ordinary least squares.

that being from the metals industry, using related metals technology and utilizing unrelated metals technology did not significantly affect the degree of local customer linkages. The lack of significant findings would suggest that plants using related metals technology no longer regard the region as an important customer market for their products, especially due to the decline of the local metals industry and the wider restructuring of the UK manufacturing sector (WATTS *et al.*, 2003).[9] In response to the decline of the local metals industry and the evolution of global supply chains, many plants were now more reliant upon international customer markets, especially to Europe and North America, and increasingly Asia (HUMPHREY and SCHMITZ, 2002; WOOD *et al.*, 2004).

Local capital investment suppliers

In addition, it was also investigated whether plants in the metals industry were more likely to acquire capital investment products, such as machine tools, manufacturing dies, machinery equipment, production technology, process machinery and industrial machines, from local suppliers within the city-region. The results from the multivariate logistic regression models shown in Table 5 (that is, Models 1–3) illustrate that plants from the metals industry are more likely to use local capital investment suppliers in comparison with unrelated industries within the manufacturing sector of the city-region ($p < 0.10$). Contrary to expectations, no significant effect was found for plants using related metals technology ($p =$ n.s.), whereas the plants that use unrelated metals technology are more likely to use local capital investment suppliers ($p < 0.05$). One possible reason for this finding is that the plants using unrelated metals technology prefer to use the local supplier market to access specialist capital equipment because they lack the internal technological capabilities, especially in related technological fields, to develop their own machine tools, specialist equipment and bespoke machinery. For example, those plants that produce bespoke products on an engineer-to-order (ETO) basis are less likely to use local capital investment suppliers (that is, Models 1–3 in Table 5), which would suggest that these plants have the internal technological capabilities to develop their own specialist machine tools and equipment.

Local service suppliers

Attention now turns to the results for Hypothesis 5, which sought to examine whether plants that use related metals technology are more likely to use local service suppliers within the city-region. The results from the multivariate logistic regression models in Table 5 (that is, Models 4–6) reveal that local service suppliers do tend to be used by plants in the metals industry ($p < 0.05$), but that this is more common amongst plants that use unrelated metals technology ($p < 0.05$) rather than those that use related metals technology ($p =$ n.s.).[10] One potential explanation for these findings is that plants that specialize in unrelated metals technology lack certain internal technological capabilities due to their specialization in an unrelated technological field, and therefore have to use local technology service suppliers instead. Examples of technological services that are acquired locally within the city-region range from metallurgical testing and machinery maintenance to scientific expertise, engineering advice and technical support.

Local knowledge spillovers

Finally, the study investigated the relationship between technological relatedness and the likelihood of receiving local knowledge spillovers from within the city-region. The empirical results from the multivariate logistic regression models shown in Table 6 (that is, Models 1–3) reveal no statistically significant relationship between the metals industry and whether a plant has received a local knowledge spillover ($p =$ n.s.). However, upon closer examination it appears that there is a clear distinction when one takes into account technological relatedness. Although plants that use related metals technology are more likely to receive local knowledge spillovers, a positive relationship that is statistically significant at the 99% level ($p < 0.01$), plants that use unrelated metals technology have a lower likelihood of receiving local knowledge spillover, with a significant negative relationship ($p < 0.01$).[11] These findings illustrate that local knowledge spillovers are primarily confined to plants whose technology is related but not too distant from the technology developed within the metals agglomeration, which may

Table 5. Multivariate logistic regression models for the estimation of sourcing from local capital investment suppliers and local service suppliers

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Explanatory variables						
Metals industry	0.82*	–	–	1.11**	–	–
Related metals technology	–	−0.08	–	–	−0.10	–
Unrelated metals technology	–	–	0.85**	–	–	1.33**
Control variables						
Plant size	−0.05	0.00	0.03	0.91**	0.98**	0.93**
Plant history	−0.13	−0.14	−0.13	−0.34	−0.35	−0.33
Local ownership	0.43	0.26	0.47	−0.41	−0.62	−0.47
Original equipment manufacturing (OEM) plant	−0.62	−0.64	−0.70	0.62	0.58	0.55
Engineer-to-order (ETO)	−1.22**	−1.05*	−1.03*	0.62	0.81	0.90
Product innovation	0.33	0.21	0.16	−0.08	−0.19	−0.25
(Constant)	−0.02	−0.07	−0.57	−2.49	−2.64	−2.90
−2 Log-likelihood	100.55	103.04	100.27	76.67	80.36	75.81
χ^2	8.34	5.86	8.63	18.63***	14.94**	19.49***
Cox and Snell R^2	0.10	0.08	0.10	0.21	0.17	0.22
Nagelkerke R^2	0.13	0.10	0.14	0.30	0.25	0.31
n	79	79	79	79	79	79

Note: Models 1–3: source from local capital investment suppliers; Models 4–6: source from local service suppliers. *Statistically significant at the 90% level; **statistically significant at the 95% level; and ***statistically significant at the 99% level (one-tailed tests).

Table 6. Multivariate logistic regression models for the estimation of receiving local knowledge spillovers and providing local knowledge spillovers

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Explanatory variables						
Metals industry	0.12	–	–	0.21	–	–
Related metals technology	–	2.19***	–	–	1.33**	–
Unrelated metals technology	–	–	−1.60***	–	–	−0.75*
Control variables						
Plant size	−0.29	−0.49	−0.32	−0.09	−0.20	−0.10
Plant history	0.25	0.28	0.23	−0.08	−0.09	−0.10
Local ownership	0.43	0.42	0.12	0.47	0.41	0.27
Original equipment manufacturing (OEM) plant	−0.25	−0.09	−0.21	−0.62	−0.55	−0.62
Engineer-to-order (ETO)	−0.01	−0.54	−0.05	−0.85	−1.20*	−0.90
Product innovation	0.44	0.96*	0.58	0.28	0.54	0.32
(Constant)	−0.03	1.22	−0.16	0.21	0.21	0.45
−2 Log-likelihood	94.04	82.66	86.53	102.13	97.45	100.14
χ^2	4.58	15.96**	12.09*	4.52	9.20	6.51
Cox and Snell R^2	0.06	0.18	0.14	0.06	0.11	0.08
Nagelkerke R^2	0.08	0.26	0.20	0.08	0.15	0.11
n	79	79	79	79	79	79

Note: Models 1–3: whether the plant has received local knowledge spillovers; Models 4–6: whether the plant has provided local knowledge spillovers. *Statistically significant at the 90% level; **statistically significant at the 95% level; and ***statistically significant at the 99% level (one-tailed tests).

indicate the existence of related knowledge spillovers that represent a form of related externality (BOSCHMA and FRENKEN, 2011a).

CONCLUSIONS

Building upon the Evolutionary Economic Geography literature (BOSCHMA and LAMBOOY, 1999; BOSCHMA and FRENKEN, 2006), this article has sought to explore the relationship between technological relatedness and Marshallian agglomeration economies by re-examining the Sheffield metals cluster that MARSHALL (1890) studied. Prior research suggests that technological relatedness is an important determinant of firm survival and cluster evolution, but to date few studies have examined its effect on Marshallian agglomeration economies within the context of a declining cluster during the later stages of the industry life cycle (NEFFKE *et al.*, 2011a). To begin with, evidence is found that the mechanisms underlying Marshallian agglomeration economies continue to be present within the declining metals industry as industry-specific localization economies (GLAESER *et al.*, 1992), and comparatively little evidence is found that external economies are present in unrelated industries (JACOBS, 1969). At first glance, this illustrates that throughout its history the city-region has been subject to a high degree of path dependency and lock-in to the technological trajectory of the metals industry life cycle. However, upon closer examination it is clear that Marshallian agglomeration economies have evolved to become more prevalent amongst plants that use related metals technology, which is a combination of ferrous metal technological know-how developed within the agglomeration with metals technology from technologically related industries. The more technologically related plants are to the pre-existing technology that was developed within the agglomeration, the more likely they are to experience the mechanisms underlying Marshallian agglomeration economies within the city-region. The findings echo similar research conclusions by NEFFKE *et al.* (2012, p. 489), who emphasized that 'it seems unrealistic that only plants in the same industry give rise to localization externalities'.

Overall, the results from the multivariate regression analysis broadly support the research hypotheses. First, this study identifies the fact that highly skilled employees can often be found within plants that have evolved to become specialists in related metals technology, which may indicate the presence of a local pool of 'related skills' that exists amongst technologically related industries within the city-region (BOSCHMA *et al.*, 2009). In a similar vein, these findings support recent research by NEFFKE *et al.* (2012) that highlights the importance of skill relatedness to the survival of firms and clusters, and the evolution of technologically related industries. Second, it is found that plants using related metals technology source a greater proportion of their materials and components, by value, from local suppliers within the city-region. Although evidence is found that plants that have developed specialisms in related technological fields continue to source locally, it should also be noted that in general these local supplier linkages are comparatively weak (GRABHER, 1993; WATTS *et al.*, 2003; SADLER, 2004). Instead it is found that managers continue to source from price-uncompetitive local suppliers in order to access their specialist technological know-how, engineering advice and technical support (CRONE and ROPER, 2001). However, mixed results are found for the propensity to source from local customers, local capital investment suppliers and local service suppliers, which supports MARSHALL's (1890) original agglomeration theory and its emphasis on a trinity of agglomeration economies: a local pool of skilled labour, local supplier linkages and local knowledge spillovers. Finally, the results from the multivariate analysis illustrate that plants using related metals technology have a greater likelihood of receiving local knowledge spillovers within the city-region. These findings support BOSCHMA and FRENKEN's (2011b) argument that technological relatedness is an important determinant of local knowledge spillovers, and that the presence of related knowledge spillovers may be being detected.

However, it is important to recognize that these results are not definitive evidence that the mechanisms underlying Marshallian agglomeration economies continue to operate within the city-region, especially as the agglomeration has declined over time with the evolution of the industry life cycle (POTTER and WATTS, 2010). Detailed longitudinal research by NEFFKE *et al.* (2008) has found that localization externalities within the UK have declined since the mid-nineteenth century leading to the deconcentration of industries and the creation of declining clusters. Another limitation is that the investigation follows MARSHALL's (1890) approach by focusing on larger manufacturing plants in the local manufacturing sector, without paying closer attention to the smaller firms and the service sector, which account for the majority of economic activity in the city-region (EUROPEAN COMMISSION, 2005). A further limitation is that, like MARSHALL's (1890) research, this article conducts a cross-sectional analysis of the metals agglomeration, as detailed longitudinal data that chart the evolutionary dynamics of the metals agglomeration were not available (PROPRIS and LAZZERETTI, 2007, 2009).

Given the importance of technological relatedness to cluster evolution, future research is needed to investigate which managerial factors and institutional factors encourage and inhibit firms from adapting and diversifying into technologically related industries (BOSCHMA and FORNAHL, 2011; MARTIN and SUNLEY, 2011). Rather than straying far from their core technological competencies, managers should adopt a long-term survival strategy that focuses on specializing in technologically related industries with comparatively lower market entry barriers in order to increase their survival within a declining agglomeration. Finally, future research is required to explore how different evolutionary processes caused the metals industry to evolve from an industry-specific agglomeration to a cluster of technologically related industries within which firms specialize in different but interrelated technological niches (BOSCHMA and FRENKEN, 2011b). In particular, the presence of technologically related industries may explain the regional resilience of the Sheffield metals agglomeration and its continued survival despite the decline of the metals industry, especially since many other Marshallian industrial districts have disappeared from the economic landscape (SIMMIE and MARTIN, 2010). Finally, future research needs to explore the importance of regional branching (BOSCHMA and FRENKEN, 2011a), especially since one of the main reasons for the continued survival of the Sheffield metals industry was the invention of stainless and specialist steels, which occurred from the interactions between technologically related industries within the city-region.

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APPENDIX A

Table A1. *Correlation matrix between the independent variables*

	1	2	3	4	5	6	7	8	9
1. Metals industry	1								
2. Related metals technology	0.44***	1							
3. Unrelated metals technology	0.61***	−0.44***	1						
4. Plant size	0.17	0.12	0.06	1					
5. Plant history	−0.06	−0.04	−0.03	−0.16	1				

(*Continued*)

Table A1. *Continued*

	1	2	3	4	5	6	7	8	9
6. Local ownership	−0.25**	−0.04	−0.22*	−0.47***	0.00	1			
7. Original equipment manufacturing (OEM) plant	−0.10	−0.17	0.05	−0.27**	0.06	0.11	1		
8. Engineer-to-order (ETO)	0.11	0.19*	−0.05	−0.11	0.03	−0.01	−0.08	1	
9. Product innovation	−0.09	−0.21*	0.09	0.17	0.06	−0.06	0.01	−0.01	1

Note: *Statistically significant at the 90% level; **statistically significant at the 95% level; and ***statistically significant at the 99% level (one-tailed tests).

Table A2. *Definitions and summary statistics of the dependent and independent variables*

Variable	Description	Details	
Dependent variables			
Highly skilled labour	Per cent of employees trained at university degree level (or to the industry's equivalent standard) such as formally qualified engineers, researchers, technologists or scientists	Mean = 50%	SD = 29%
Local supplier linkage	Per cent of expenditure on materials and components spent locally with suppliers within the city-region	Mean = 17%	SD = 25%
Local customer linkage	Per cent of sales turnover from local customers within the city-region	Mean = 8%	SD = 14%
Local capital investment suppler	Plant sources from a local capital investment supplier within the city-region (for example, machine tools, manufacturing dies, machinery equipment, production technology, process machinery or industrial machines)	Yes = 46%	No = 54%
Local service supplier	Plant sources from local service suppliers within the city-region (for example, technological, maintenance, consultancy, accounting or financial services)	Yes = 71%	No = 29%
Local knowledge spillover	Received a local knowledge spillover from within the city-region within the past three years	Yes = 32%	No = 68%
Explanatory variables			
Metals industry	Plant operates in the metals industry (that is, either ferrous or non-ferrous metal)	Yes = 62%	No = 38%
Related metals technology	Plant uses related metals technology from the ferrous metals industry (that is, metals that primarily contain iron, such as pure iron, alloys, steel and stainless steel)	Yes = 24%	No = 76%
Unrelated metals technology	Plant use unrelated metals technology from the non-ferrous metals industry (that is, metals that do not contain iron, such as copper, tin, aluminium, zinc, brass, platinum, silver and gold)	Yes = 38%	No = 62%
Control variables			
Plant size	Number of employees on the payroll register at the site (log)	Mean = 5.04	SD = 0.89
Plant history	Number of years since the company was first established at this site (log)	Mean = 2.69	SD = 1.34
Local ownership	Plant is owned locally (that is, headquarters within the city-region)	Yes = 51%	No = 49%
Original equipment manufacturing (OEM) plant	Plant is an OEM, rather than a first-, second- or third-tier supplier	Yes = 57%	No = 43%
Engineer-to-order (ETO)	Plant uses ETO manufacturing systems rather than build-to-stock (BTS) or build-to-order (BTO)	Yes = 23%	No = 77%
Product innovation	Plant has introduced a new product innovation that is new to the firm and industry in the past three years	Yes = 51%	No = 49%

NOTES

1. LQ analysis (that is, manufacturers by employment size band, South Yorkshire compared with the national average): 50–99 employees (LQ = 1.25), 100–199 employees (LQ = 1.50), 200–499 employees (LQ = 2.00), and 500–999 employees (LQ = 1.25).
2. A number of studies within the regional studies literature have used longitudinal data, hazard models and organizational ecology models to analyse the birth, entry, exit and evolution of firms within an industrial cluster. Notable recent examples include PROPRIS and LAZZERETTI's (2007) study of the Birmingham jewellery Marshallian industrial district; HEEBELS and BOSCHMA's (2011) study of book publishers in the Netherlands; and research by BOSCHMA and LEDDER (2009) into the evolution of the Amsterdam banking cluster. Unfortunately, due to the exceptionally long history of the Sheffield metals industry, whose origins date back to the seventeenth century, longitudinal data that chart the evolution of different firms throughout the entire history of the Sheffield metals industry were not available. Therefore, as this research focuses on empirically investigating the relationship between technological relatedness and agglomeration economies within the context of a declining industrial cluster, it was more appropriate that detailed cross-sectional data from the city-region were collected and analysed. Such an approach was used successful by a number of scholars within the regional studies literature, including GRABHER (1993), SADLER (2004), and PROPRIS and WEI (2007).

3. Representative checks were conducted using two-tailed Pearson's chi-square (χ^2) tests; no presence of response bias was found for industry or location in the region, but it is important to highlight that larger plants were over-represented:

   Representative test (location): $\chi^2 = 2.0$; critical value = 7.82; d.f. = 3; $p = 0.05$ (two-tailed test).
   Representative test (industry): $\chi^2 = 1.97$; critical value = 7.82; d.f. = 3; $p = 0.05$ (two-tailed test).
   Representative test (size): $\chi^2 = 20.34$; critical value = 5.99; d.f. = 2; $p = 0.05$ (two-tailed test).
4. Using tests from the econometric literature, it was found that multicollinearity was not an issue in the multivariate regression models (GREENE, 2008). According to HILL and ADKINS (2001), multicollinearity becomes a concern when variance inflation factors (VIF) exceed 6. In all cases, VIF statistics were below 2, indicating that multicollinearity problems are unlikely to be present within the empirical analysis (GREENE, 2008). Furthermore, the results from the correlation matrix between independent variables shown in Table A1 in Appendix A illustrate a lack of multicollinearity concerns. Overall, these findings suggest that multicollinearity problems are unlikely to affect the empirical analysis.
5. Using established econometric notations, the multivariate tobit regression models are expressed as follows:

$$Y_i = \begin{cases} L_i & \text{if } X_i\beta + \varepsilon_i \le L_i \\ X_i\beta + \varepsilon_i & \text{if } L_i < X_i\beta + \varepsilon_i < U_i \\ U_i & \text{if } X_i\beta + \varepsilon_i \ge U_i \end{cases}$$

   where Y_i is the dependent variable: a censored interval variable between L_i (that is, 0%) and U_i (that is, 100%) used for dependent variables such as highly skilled labour, local customer linkage and local supplier linkage; and $X_i\beta$ is the explanatory variable, β_1; plant size, β_2; plant history, β_3; local ownership, β_4; original equipment manufacturing (OEM) plant, β_5; engineer-to-order (ETO), β_6; and product innovation, β_7.
6. Using established econometric notations, the multivariate logistic regression models are expressed as follows:

$$P(\text{LKS} = 1) = \frac{1}{1 + e^{-(\beta_0 + \beta_1(explanatory)_i + \beta_2(size)_i + \beta_3(history)_i + \beta_4(owner)_i + \beta_5(OEM)_i + \beta_6(ETO)_i + \beta_7(innovation)_i + \varepsilon_i)}}$$

   where LKS is a dichotomous dependent variable, such as whether the plant sources from local capital investment suppliers, sources from local service suppliers or receives local knowledge spillovers; and β_{1-7} is the explanatory variable, β_1; plant size, β_2; plant history, β_3; local ownership, β_4; OEM plant, β_5; ETO, β_6; and product innovation, β_7.
7. Table 2 also shows that older plants relied less heavily on a local pool of skilled labour, a result that may be capturing the effect of the oldest plants, whose products have become standardized and require a less skilled workforce, although this relationship was only significant at the 90% level ($p < 0.10$). As expected, plants that ETO ($p < 0.05$) and have created a product innovation ($p < 0.10$) were more likely to depend upon skilled labour, indicating that within a declining agglomeration the local skills base may still be an important source of innovation. In accordance with the approach of SMITH and BRAME (2003), a series of multivariate OLS regression models were created to test the validity of the results from the tobit models (Table 2) (BARKLEY and MCNAMARA, 1994). The results from the OLS models were found to be similar to the multivariate tobit models, with the positive relationship between the metals industry ($p < 0.05$), related metals technology ($p < 0.01$), and the skill level of employees remaining statistically significant.
8. In addition, Table 3 also shows that larger plants are less likely to source locally ($p < 0.05$), a result that is similar to previous empirical studies (BARKLEY and MCNAMARA, 1994), and that locally owned plants have reduced their degree of local supplier linkage ($p < 0.05$). Many of the managers interviewed from locally owned plants commented that they had reduced local supplier linkages because local suppliers were often price uncompetitive.
9. It is found that locally owned plants are more likely to maintain local customer linkages ($p < 0.01$), which, together with the results that local ownership is negatively related to the degree of local supplier linkages, suggests that locally owned plants maintain their local customer linkages but have switched to sourcing supplier inputs from lower-cost suppliers located outside the city-region (Table 4).
10. As expected, it was also observed that larger plants are more likely to acquire services from local suppliers within the city-region ($p < 0.05$) (that is, Models 4–6 in Table 5).
11. In addition, it is also found that product innovation increases the likelihood of receiving local knowledge spillovers ($p < 0.10$), which suggest that research and development spillovers may be occurring within the declining cluster, and are not confined to the earlier stages of the life cycle as the literature suggests (AUDRETSCH and FELDMAN, 1996). However, it is found that ETO has a negative effect with local knowledge spillovers, albeit at the 90% level of significant ($p < 0.10$). Furthermore, to improve measurement validity, sensitivity analysis using a similar measure for receiving local knowledge spillover was also conducted: whether the plant provided local knowledge spillovers within the region (that is, Models 4–6 in Table 6). Within Table 6 the empirical results for providing local knowledge spillovers (that is, Models 4–6) are similar to those for receiving local knowledge spillovers (that is, Models 1–3). For example, it is found that plants that use related metals technology are more likely to provide local knowledge spillovers ($p < 0.05$), but that those plants using unrelated metals technology are less likely to provide knowledge locally ($p < 0.10$).

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