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QUANTIFYING KNOWLEDGE SPILLOVERS FROM THE UK CREATIVE INDUSTRIES

A scoping study

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CONTENTS

EXECUTIVE SUMMARY

The creative industries have been identified by government as a sector of key interest and a critical driver of innovation and growth. The sector is of interest not just for its own growth potential, but because of the wider perceived spillover benefits from the creative industries onto other firms and local environments.

It is important to understand these spillover effects – in particular, what spillovers exist, the mechanisms through which they occur, and the size of the impacts they create – since there may be a strong case for government policy to financially support activities in the creative industries that generate these positive benefits. Yet measuring spillovers is notoriously difficult. The Department for Digital, Culture, Media and Sport (DCMS) commissioned Frontier Economics to conduct a scoping exercise to understand how knowledge spillovers from the creative industries could be quantified, and whether existing UK data sources would be suitable for such empirical analysis. This report presents the results of this scoping study and recommendations going forwards.

WHAT ARE KNOWLEDGE SPILLOVERS

Spillovers are benefits (or costs) of an activity that accrue not to the individual or business undertaking the activity but to other individuals or businesses. Knowledge spillovers are new ideas, innovations or processes that are created by one individual or firm, but that can be used by another (without full compensation for the benefit of that being paid to the creator). Knowledge spillovers could occur through the intentional sharing of knowledge, or through labour movements or through reverse engineering of observed outputs. The spillovers could be between firms in the same industry or different industries.

Qualitative research, case studies and anecdotal evidence suggest that the creative industries are highly innovative. This would create significant potential for knowledge spillovers. However, the existing literature and our own discussions with many individuals who work in or with the creative industries have stressed that much innovation is derived from everyday activity and problem solving, rather than specific investment with the objective of generating innovation. This is a particular challenge when it comes to quantifying knowledge spillovers.

HOW TO QUANTIFY SPILLOVERS

Based on a review of the economics literature we believe that the technically preferred way of quantifying knowledge spillovers is to estimate an 'augmented production function'. This focusses on firms who are expected recipients of knowledge spillovers, and examines whether 'external knowledge' (i.e. created by the creative industries) has any impact on their output after controlling for the firms' own inputs (in terms of their labour, capital and own knowledge inputs). A positive impact of external knowledge on recipient firms' output reveals that there are spillover benefits from the knowledge created by external firms.

The main complexity of this approach is defining the external knowledge that is relevant to each recipient firm. In this context it would be calculated as a weighted aggregate of the knowledge stock of creative industry firms, where the weights would be designed to capture the proportional knowledge flows between the creative industries and the recipient firm. These weights could be based on geographical proximity (i.e. spillovers are assumed to be greater for firms that are closer together), industry (i.e. spillovers are assumed to be greater for firms that are linked to the creative industries through their supply chains, or who see lots of labour turnover between themselves and the creative industries), combinations of geography and industry, or on many other factors.

Estimating a relationship of this source requires good data. In particular, one needs:

- Data on the output and inputs of a large sample of recipient firms, including data on their own 'knowledge' (which is typically assumed to derive from investments in innovation)
- Data on the stock of 'external knowledge' for these firms, which requires data on spending on innovation by the creative industries, and data that is believed to be indicative of the knowledge flows between the creative industries and recipient firms.

Ideally this would be available for multiple time periods to allow unobservable characteristics of firms to be controlled for.

UK DATA SUITABILITY

We do not believe that existing UK data sources are sufficient to enable knowledge spillovers from the creative industries to be quantified using the technically preferred production function approach.

It is possible in principle to get the required data on recipient firms by linking together data on output and labour/capital inputs from the Business Structures Database or the Annual Business Survey (ABS) with data on R&D spending or innovation activity from Business Enterprise Research and Development (BERD) or the UK Innovation Survey (UKIS). Different combinations may be preferable depending on which recipient firms are of particular interest.

However, we do not believe that sufficient data are currently available on the external knowledge stock being created by the creative industries. BERD and UKIS have only small samples of firms from the creative industries each year, which means it is not possible to calculate robust estimates of innovation spending at anything less than a national or regional level. Without estimates of innovation at finer geographical levels (such as for travel-to-work areas or local authority districts) it is not possible to get enough variation in the external knowledge that recipient firms are exposed to in order to allow the robust estimation of the effect of external knowledge on recipient firms' output.

It is also not possible to investigate spillovers between firms in the creative industries using existing UK data, as there are neither enough creative industry firms observed in the ABS, nor sufficiently detailed data on innovation by creative industry firms.

OPTIONS FOR FUTURE ANALYSIS

There are three main options when it comes to trying to quantify knowledge spillovers from the creative industries. The first would yield the most robust estimates but requires new data collection that is costly and time consuming. The second option is quicker to implement but attribution is more challenging to establish. The third option is to directly ask people to identify spillovers which has the advantage of being conceptually simpler, albeit data gathered using this approach may be less reliable.

Option 1: Collect additional data to facilitate a production function approach

New data could be collected to enable implementation of the technically preferred 'augmented production function' approach. The data required would be expanded data on the innovation spending and activity of creative industry firms, with a particular focus on increasing the sample size in fine geographical areas. It would also be beneficial to collect sufficient data to be able to produce robust estimates of innovation at the sub-sector level within each geography.

This option would yield the most robust and broad-based estimates of the size of knowledge spillovers from the creative industries. However, the new data required would be time consuming to collect and very costly (a preliminary estimate of costs indicates in excess of £250,000 for survey work alone) given the number of firms that would need to be sampled. Furthermore, while these new data would enable a production function approach, there would still be limitations. Some innovation in the creative industries may be missed if individuals underreport their investments or innovation, and the collected data may not be truly representative if the self-employed are innovative and not surveyed. This would risk biasing estimated spillovers downward. It would also still not be feasible to estimate spillovers within the creative industries using this approach.

Option 2: Examine associations between creative industry activity and other firms' performance

In the absence of being able to collect new data on creative industry firms' innovation, an alternative empirical approach is to estimate the impact of creative industry activity on other firms' output or innovation. This approach has the advantages that data on the activity of creative industry firms is easier to come by, and therefore this method is quicker and considerably cheaper to implement, and the spillovers from 'hidden innovation' would not be missed by only focussing on measurable innovation spending. The main difficulty with this approach is being able to convincingly argue that any observed correlation between creative industry activity and other firms' output or innovation is because of spillovers from the creative industries rather than any other unobserved factor. This requires a carefully thought-out empirical strategy. Despite the limitations such analysis would add considerably to the current evidence base, and be considerably cheaper than option 1, likely in the region of £60,000 - £80,000.

Option 3: Other bespoke data collection

A final alternative is to conduct more bespoke data collection that is explicitly focused on measuring spillovers. For example, one could attempt to survey business about how much they have benefitted from knowledge created in the creative industries. However, it is extremely challenging to design such questions in such a way that people could reliably respond, and such data does not lend itself easily to being able to quantify the prevalence or total value of spillovers across the creative industries as a whole.

RECOMMENDATION

DCMS wishes to pursue a quantitative assessment of the spillover benefits of the creative industries, whether from innovation specifically or more generally. Our recommendations are three-fold:

1. We recommend they commission research to examine in detail the correlation between creative industry activity and other firms' outcomes (option 2). This would yield valuable evidence on possible spillover benefits from the creative industries relatively quickly and at relatively low cost.

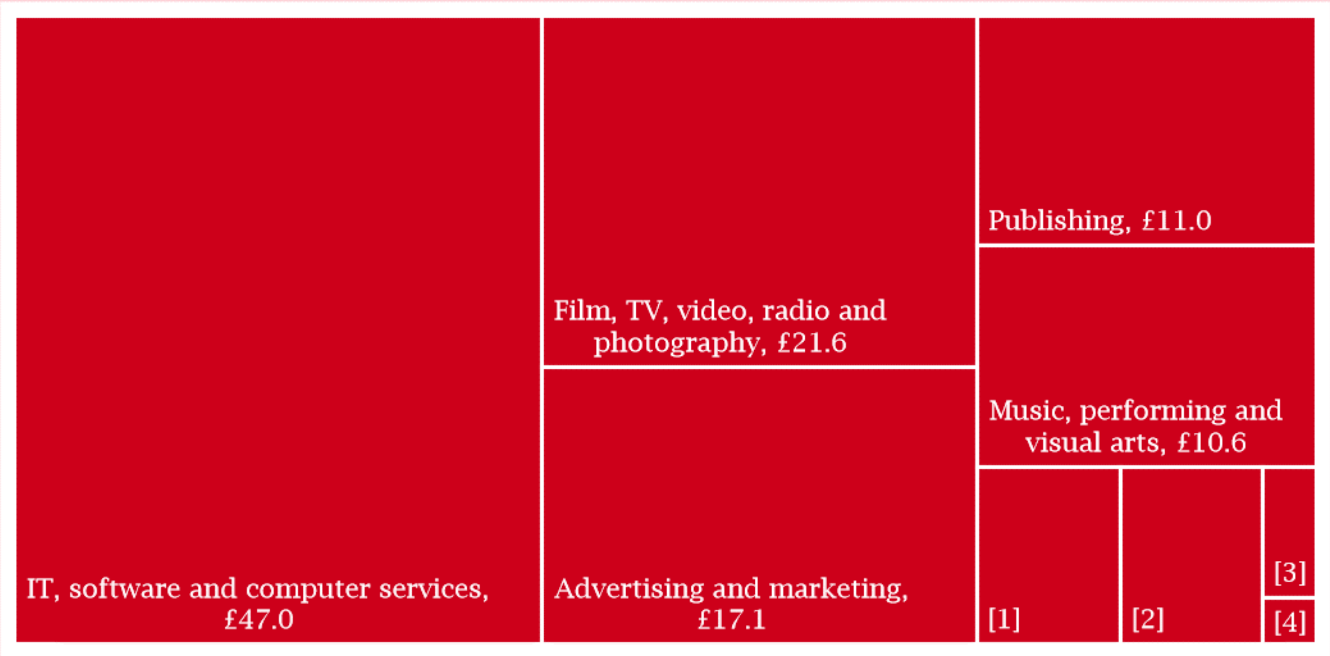
2. We feel that the cost of collecting comprehensive data on innovation spending by creative industry firms (option 1) is prohibitively expensive. However, where such data can be more easily collected – for example, as a condition of firms' receiving public funding – we would recommend that this is instigated. Over time this will gradually build a valuable data resource that could be used in future.

3. Related to the above, where new government programmes are being rolled out or introduced which cover the creative industries, we recommend that data is collected before, during and after implementation with a view to quantifying the impact of the programme both on treated firms and more widely in the local area.

1 INTRODUCTION

The government has identified the creative industries as a sector of key interest and a critical driver of innovation and growth.[1] In 2019 the creative industries contributed £115.9 billion of gross value added (GVA) to the UK economy in 2019, over 5% of total UK GVA.[2] The relative contribution of the 9 subsectors that make up the creative industries is illustrated in Figure 1.

FIGURE 1 CONTRIBUTINO OF THE CREATIVE INDUSTRIES TO UK GROSS VALUE ADDED IN 2019



Source: DCMS Sectors Economic Estimates, February 2022

Note: Figures are in £ billion. [1] is Architecture (£3.6 billion), [2] is "Design and designer fashion" (£3.6 billion), [3] is "Museums, galleries and libraries" (£1.0 billion) and [4] is "Crafts" (£0.4 billion).

Between 2011 and 2019 the GVA of creative industries grew by 41%, twice as fast as the UK economy as a whole (which grew by 16%). The creative industries are expected to have high growth potential going forwards, in particular because they are relatively innovative (Bakhshi, 2022, Gkypali and Roper 2018), resistant to automation (Bakhshi, Frey and Osborne 2015), and relatively export orientated[3]. The creative industries are also important from the perspective of the government's levelling up agenda, as there are clusters of creative industry activity found across the UK – in particular, outside of London and the South East (Mateos-Garcia and Bakhshi (2016).

The creative industries are of interest not just for the growth potential of the sector itself, but also for their potential to have wider spillover benefits on other firms and local environments. These spillovers are important, because they will not be factored into the decisions being made by the firms generating them. This means that individual firms may be undervaluing – from the viewpoint of wider society - some of their activities, and therefore not undertaking as much of them as society might like. It is important to

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[1] HM Treasury (2021) 'Build Back Bette: our plan for growth'

[2] Activity in 2020 and 2021 was depressed due to the Covid-19 pandemic, however in 2021 the creative industries still contributed over 5% of total UK GVA. (DCMS Economic Estimates February 2022).

[3] DCMS Sectors Economic Estimates

understand these spillover effects – in particular, what spillovers exist, the mechanisms through which they occur, and the size of the impacts they create – since there may be a strong case for government policy to financially support activities in the creative industries that generate these positive benefits.

While there has been discussion of, and some attempts to quantify, spillover benefits from the creative industries, robust evidence on this important area is still lacking (TFC Consultancy, 2015). The Department for Digital, Culture, Media and Sport (DCMS) therefore commissioned Frontier Economics to conduct a scoping exercise to understand the extent to which it would be possible to use existing publicly available data to quantify the existence and size of knowledge spillovers from the creative industries in the UK.

The structure of this report is as follows. In section 2 we present a framework for spillovers from the creative industries, and define 'knowledge spillovers' which are the focus of this scoping study. In section 3 we discuss the main method commonly used in the empirical economics literature to quantify the size of knowledge spillovers, and in in section 4 we discuss whether currently available UK data are sufficient to implement this approach. In section 5 we briefly discuss some other approaches that could be employed. We conclude in section 6 with some recommendations for policymakers and researchers interested in this topic.

2 A CONCEPTUAL FRAMEWORK FOR SPILLOVERS

The term 'spillovers' is used by economists to refer to the benefits (or costs) of an activity that accrue not to the individual or business undertaking the activity but to other individuals or businesses. For example, in the creative industries context, an example could be a fashion designer who comes up with a new way of weaving fabric that makes the material stronger. While this is valuable to the designer who, can charge a higher price for their higher quality product, it is also valuable to industrial textile firms who are able to acquire the knowledge of the new weaving process through reverse engineering. There is a spillover benefit to the industrial textile firms, from which the fashion designer receives no reward.

The presence of such spillovers is important because it can provide an important justification for the government to financially support spillover-generating activities. Businesses generally act in their own self-interest, undertaking activities if they bring more benefits to the business than they cost. In doing such calculations, they do not take into account the wider benefits that accrue to other firms or individuals. This means that an activity may not be undertaken, because the private benefits to the firm do not exceed the costs, even though the total benefits to the economy or society may exceed the costs of the firm undertaking the activity. In such circumstances it may be beneficial for society if the government were to support some of the cost of the activity so that it takes place.

2.1 CATEGORIZING SPILLOVERS

There are many different mechanisms through which the benefits (or costs) of an activity can be felt more widely than the firm undertaking the activity. One way of grouping spillovers, based on Jaffe (1996) is:

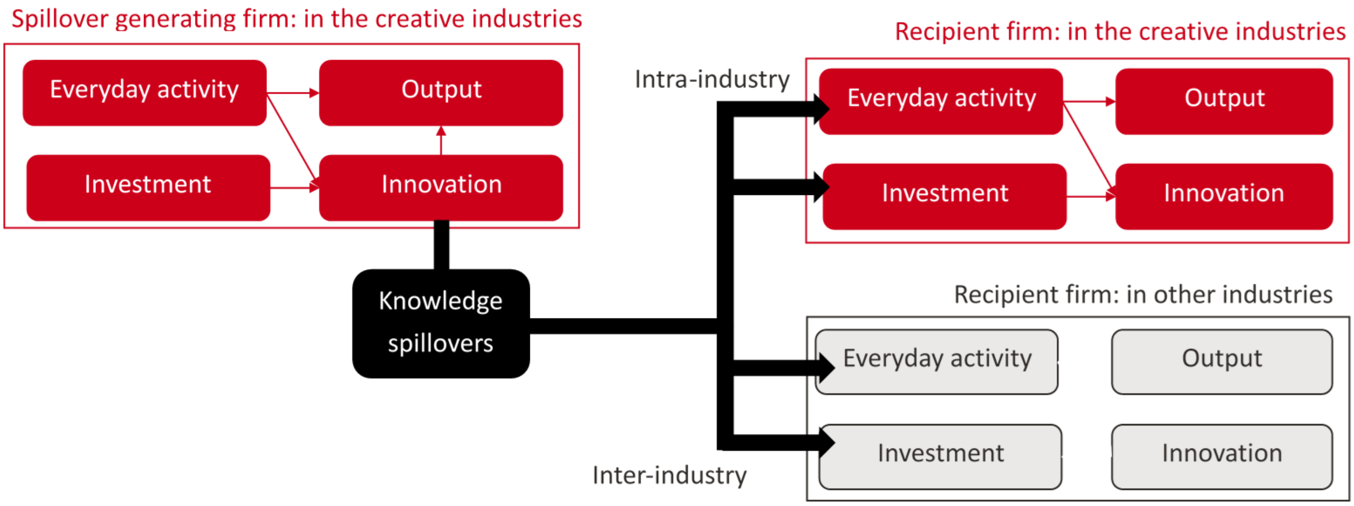
- **Knowledge spillovers**: These are new ideas, innovations or processes that are created by one firm, but that can be used by another (without full compensation for the benefit of that being paid to the creating firm). Knowledge spillovers could occur through the intentional sharing of knowledge, or through labour movements or through reverse engineering of observed outputs. The spillovers could be between firms in the same industry (intra-industry) or different industries (inter-industry).
- **Market spillovers**: These result when market forces cause some of the benefit from new products or processes to be felt more widely than the creating firm. For example, if a new product caused other firms to lose market share, or if a new process resulted in some workers being made redundant, then these would be examples of negative market spillovers. Alternatively, if a new product was developed and sold for less than consumers valued it, then this would be a positive market spillover.
- **Network spillovers**: This includes what have been termed 'coordination', 'clustering' and 'agglomeration' spillovers. Coordination spillovers are those where the benefit of an action is dependent on the actions of others – for example, the value of a new computer operating system is dependent on applications being written for it. Clustering spillovers occur when firms enjoy benefits from being located closely together, for example because it increases knowledge spillovers or increases innovation. Agglomeration spillovers occur when the decision of firms to locate in a particular area has an impact on the local area – such as by encouraging other firms to locate there, increasing spending in the local area, increasing the attractiveness of the local area, or increasing tourism in an area.

2.2 KNOWLEDGE SPILLOVERS

While all the different types of spillovers are potentially important, in this scoping exercise we focus on quantifying knowledge spillovers from the creative industries. A diagrammatic representation of knowledge spillovers is set out in Figure 2. We start from a firm in the creative industries on the left-hand side. The firm invests in some research, which yields a new product innovation, which feeds through into its own output. But there is also a knowledge spillover: the knowledge in that innovation is acquired, through various possible mechanisms, by other firms, and the new innovation affects the production of their output and/or their investment activities. These 'recipient firms' may be in the creative industries themselves, or in completely different industries.

It should also be noted that in Figure 2 there is an important link between everyday activity and innovation. The existing literature on innovation in the creative industries, and our own discussions with many individuals who work in or with the creative industries have stressed that much innovation generation is practice-based – in other words, derived from every day activity rather than specific investment with the objective of generating research.[4] As will be discussed in section 4, this makes quantifying knowledge spillovers more challenging than if innovation were only derived from specific investments.

FIGURE 2 DIAGRAMATIC REPRESENTATION OF KNOWLEDGE SPILLOVERS FROM THE CREATIVE INDUSTRIES



Source: Frontier Economics

[4] For example, Green, Miles and Rutter (2007) point out that the creative industries involve much 'everyday problem solving' which leads to many small innovations that can substantially shape a final product.

3 QUANTIFYING KNOWLEDGE SPILLOVERS: PRODUCTION FUNCTION APPROACHES

There is a large economics literature that has sought to estimate the size of knowledge spillovers in a variety of settings.[5] The main approaches used we refer to as 'production function approaches'. We discuss two permutations of this methodology in this section – one that estimates the impact of knowledge spillovers directly on output, and one that estimates the impact of knowledge spillovers first on innovation and then on output. In section 5 we briefly discuss some other methodologies that could be employed.

3.1 THE EFFECT OF KNOWLEDGE SPILLOVERS ON OUTPUT

One common approach to quantifying spillovers taken in the literature is to estimate an augmented production function (following Griliches (1979)) that includes as components the knowledge stock of a firm and the knowledge stock of external firms. For an example of this approach in practice, see Li and Bosworth (2020). This methodology is described in more detail in annex A, but essentially entails estimating an equation of the form:

$$\ln y_{it} = A + \alpha \ln C_{it} + \beta \ln L_{it} + \gamma \ln K_{it} + \vartheta \ln S_{it} + e^{u_{it}}$$

where (ln denote the natural logarithm) and:

- y_{it} is the output of firm i at time t
- C_{it} is the firm's physical capital stock
- L_{it} is the firm's labour stock (number of employees or hours worked)
- K_{it} is the firm's stock of "knowledge"
- S_{it} is the stock of "external knowledge" that is relevant to firm i

The coefficient ϑ indicates the presence of knowledge spillovers: a positive ϑ would imply that the external knowledge stock has a positive benefit on firm i's output, while a negative ϑ would indicate that the external knowledge stock has a negative impact on firm i's output.

There are four key complexities with estimating this relationship in practice. The first is obtaining data on the 'stock of knowledge' – both of the firm in question and the external stock. The assumption typically used is that there is some investment activity – such as spending on R&D – that creates firm-level knowledge. The stock of knowledge at a point in time is then the previous stock of knowledge, less some amount that has depreciated, plus any new investment in knowledge. Under some assumptions the flow of new investment in knowledge can be used in place of the stock of knowledge.

The second complexity is defining the external knowledge that is relevant to the firm in question. The external knowledge measure (S_{it}) is a weighted aggregate of the knowledge stock of other firms:

$$S_{it} = \sum_{j \neq i} w_{ji} R_{jt}$$

Where R_{jt} is the 'knowledge stock' of firm j at time t, and w_{ji} are weights designed to capture the proportional knowledge flows between firm j (the source of the knowledge spillover) and firm i (the recipient firm). These weights capture the idea that knowledge flows will be more likely, or more impactful,

[5] Often the focus has been on estimating spillovers from spending on research and development (R&D), as the existence of such spillovers is an important justification for the large amount of public spending on R&D (either directly or through tax subsidy schemes) in many countries.

between some firms than others. Different approaches can be taken for these weights, reflecting different views about the mechanisms through which knowledge spillovers occur. For example, weights may be based on:

- Technological proximity. This aims to capture the idea that knowledge generation is more useful to firms that operate using similar technology.
- Product market proximity. This aims to capture the potentially negative spillovers that might occur through rivalry: an external firm may be able to use its knowledge creation to gain market share.
- Supply chain links. This aims to capture the links between companies through the supply chain – either forwards spillovers that flow from suppliers or backward spillovers that flow from buyers.
- Networks. This aims to capture links between collaborators in knowledge generation, such research collaborations between individuals employed in different firms.
- Labour force linkages. This aims to capture the idea that knowledge spillovers might occur through the movement of labour between firms.
- Geographical proximity. This aims to capture the idea that knowledge spillovers are more likely between firms that are geographically closer together.

Sometimes these different approaches are combined in single weight: for example, geographical and supply chain links, such that the external stock of firms that are both geographically close and linked through the supply chain are given more weight than the knowledge stock of firms that are linked through the supply chain but are more geographically dispersed, or the knowledge stock of firms that are geographically close but not connected through the supply chain.

A third issue concerns the length of the 'lag' between knowledge being generated and a firm's output being affected. This is true both of firms' own knowledge and external knowledge – it may take time for an innovation to bear fruit in terms of greater output. However, it is particularly an issue for external knowledge, which may take some time between being generated and being absorbed by other firms. It may therefore be theoretically desirable to control for the external knowledge in a previous period, for example S_{it-1}, when examining output in time *t* as external knowledge generated at time *t* would not have permeated yet.

The final complexity is being able to argue that any observed relationship is causal – i.e. that it is external knowledge that is affecting output – rather than just a non-causal correlation. For example, it is important to be able to rule out unobserved factors that affect both the external knowledge stock and recipient firms' output. This is always challenging, not least because unobservable productivity shocks would be expected to affect both firms' outputs and inputs into production. Various approaches are often taken here. This includes relying on lagged measures of knowledge, controlling for unobserved time or industry effects using additional control variables, controlling for unobserved firm effects using panel data, and using 'instrumental variable' approaches that make use of variables that correlate with knowledge stocks but have no direct impact on output.

To estimate the effect of knowledge spillovers on output at the firm level using this approach there are 5 main data requirements:

1. Firm level data on both output and inputs (capital and labour) for recipient firms

2 Data for the same firms on their internal stock of knowledge (under some assumptions this can be derived from the annual addition to their internal stock of knowledge).

3 Data on the relevant external knowledge stock. This does not necessarily have to be generated at the firm level (i.e. differ for every recipient firm in the data). External knowledge stocks could be calculated at the industry level, or at a geographical level, or an industry-geography level. All recipient firms in the same group (e.g. industry, geography or industry-geography group) would then be deemed to have access to the same external knowledge stock

4 Multiple years of data may be required to introduce lags between knowledge and output, and would be required in order to control for unobservable firm effects.

5 Ideally there would also be data on one or more instruments – variables that correlate with external knowledge that do not directly affect output themselves.

In section 4 we discuss the extent to which existing UK data meets these requirements.

3.2 THE EFFECT OF KNOWLEDGE SPILLOVERS ON INNOVATION

A second approach to quantifying spillovers taken in the economics literature follows the methodology of Crépon, Duget and Mairesse (1998) and is often known as the CDM model. There are several stages in this set up. The first stage models whether or not a (recipient) firm chooses to invest in innovation, and if so, how much. The second stage estimates the effect of this investment in innovation on innovation output. Knowledge spillovers often feature in this second stage, having an effect on innovation output over and above the recipient firm's own inputs into innovation. The final stage involves a production function, where the firm's output depends on its inputs (such as capital and labour), the innovation output of the second stage, and potentially again knowledge spillovers. For an example of this approach see Audretsch and Belitski (2020).

This approach is more involved than the seeking to examine the impact of knowledge spillovers on output directly using the methodology discussed in section 3.1 In particular, it requires additional data on factors that are believed to affect each stage only – for example, factors that affect firms' decisions to invest in innovation but not innovation output or firm output directly, and factors that affect innovation output that do not directly affect firms' decision to innovate or their final output.

Given these additional data requirements, we do not focus on the feasibility of implementing this approach for identifying knowledge spillovers from the creative industries. However, we do discuss the availability of data for the second stage of this model – that examining innovation production and the impact on that of external knowledge. This is because while it might be most theoretically desirable to quantify the impact of knowledge spillovers on recipient firms' outputs, it is still useful to understand the possibility of being able to quantify the impact of knowledge spillovers on recipient firms' innovation.

4 THE SUITABILITY OF UK DATA FOR IMPLEMENTING A PRODUCTION FUNCTION APPROACH

We turn now to a discussion of UK data, and the scope for using these to quantify the size of knowledge spillovers from the creative industries in the UK using an augmented production function approach.

4.1 DATA OVERVIEW

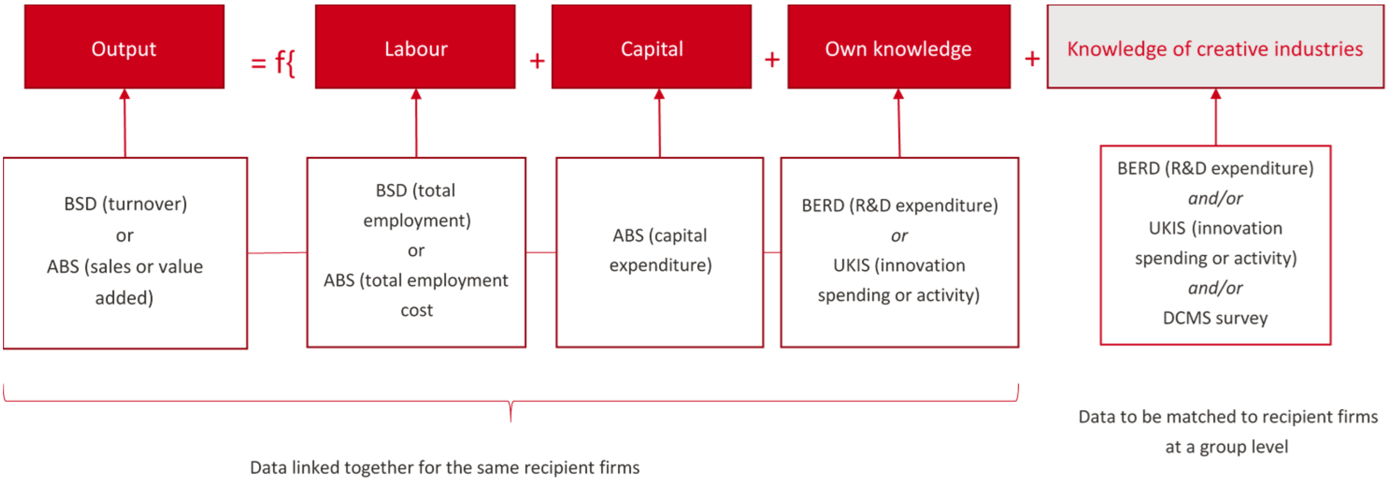
There is no one large dataset that provides data on output and inputs (including knowledge generation activities such as R&D) for firms in the UK. However, these data can be obtained by linking several sources of business data together. Specifically, some combinations of:

- **Business Structures Database (BSD)**: This annual dataset contains a small number of key variables for almost all businesses in the UK. It is derived from the Inter-Departmental Business Register, which itself is derived from PAYE and VAT records, and so around 99% of economic activity is captured. The BSD does not capture the self-employed, or those businesses with revenues below the UK sales tax threshold (£85,000 in 2021/22). The BSD contains administrative data on employment and turnover, as well as industry and detailed geography.
- **Annual Business Survey (ABS):** This is an annual survey of around 73,000 businesses in the production, construction, distribution and services industries (which represent around 2/3 of economic activity). The ABS includes high level indicators of economic activity such as total value of sales, capital spending, employment costs and approximate gross value added.
- **Business Enterprise Research and Development (BERD)**: This is an annual survey of around 5,400 business, drawn from the population known to have conducted R&D (for example, using past years of the BERD, the ABS and UKIS, or R&D tax credit recipients). The survey collects data on expenditure on R&D (in house and external) and R&D employment, and for large R&D spenders further information such as the source of funds for R&D performed and the type of R&D.
- **UK Innovation Survey (UKIS)**: This is a biennial survey of around 14,000 businesses who have at least 10 employees and who are in industrial categories B-N. (This excludes 'Agriculture, Forestry and Fishing', 'Public administration and defence', 'Education', 'Human health and social work activities', 'Arts, entertainment and recreation', 'Other service activities'.) The survey asks about investment "for the purposes of current or future innovation" through various activities. Firms are also asked whether they have introduced new or improved goods, or services or processes.
- **DCMS' survey**: In 2020 the DCMS conducted a bespoke survey of 625 firms in the creative industries. The data collected was similar to that asked by the UKIS.

Figure 3 below illustrates how these data could potentially be brought together to enable an augmented production function approach to quantifying the effect of knowledge spillovers from the creative industries on recipient firms' output. Similarly, Figure 4 illustrates how these data could be brought together to instead quantify the effect of knowledge spillovers on recipient firms' innovation output.

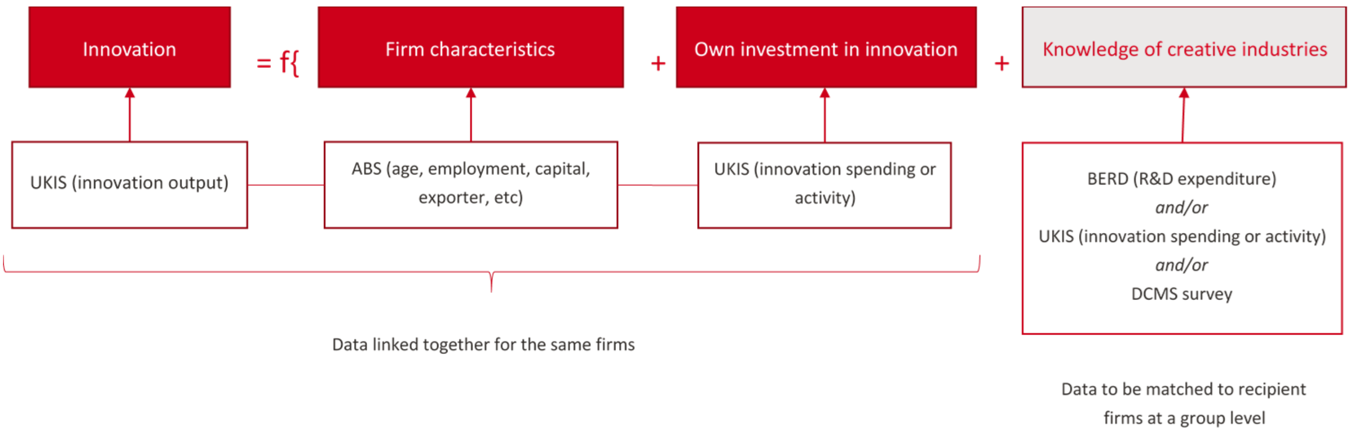
It is worth noting that while the BSD collates data on the same firms every year, the other data described above are cross-sectional surveys and the firms who are sampled changes each time the survey is conducted. (Though the BERD sample always includes the top 400 or so R&D spenders, so to the extent that a firm always stays a top R&D spender then they will be sampled ever year). This means that it is not generally possible to use panel data methods to estimate knowledge spillovers. However, it is still possible to introduce a lag between knowledge creation and output, or between the knowledge of the creative industries and recipient firms' output or innovation, through the choice of which years of cross-sectional data are matched together. For example, data from the ABS on output, capital and labour in 2014 could be matched with data on innovation spending from UKIS 2012-14.

FIGURE 3 CONTRIBUTION OF DIFFERENT DATA SOURCES TO AN AUGMENTED PRODUCTION FUNCTION



Source: Frontier Economics

FIGURE 4 CONTRIBUTION OF DIFFERENT DATA FOR ESTIMATING THE EFFECT OF KNOWLEDGE SPILLOVERS ON INNOVATION



Source: Frontier Economics

4.2 DATA ON RECIPIENT FIRMS

In terms of data on recipient firms, Figures 3 illustrates that for estimating the effect on recipient firms' output this can be obtained from either the BSD or ABS linked to either the BERD or UKIS. There are pros and cons of the different data combinations:

- Utilising the ABS has the advantage that it is possible to control for the capital input of the firms, on which there is no information in the BSD. However, this comes at the cost of sample size and representativeness, since the ABS is only a survey of firms and does not survey firms in all industries.
- Using data from BERD, the recipient firms would only be drawn from (disproportionately large) firms that are doing some R&D, while using data from UKIS the recipient firms would only be representative of firms with more than 10 employees who are in the industries surveyed by UKIS. With BERD only spending on R&D can be controlled for, while with UKIS it is possible to control for wider indicators of firms' innovation inputs.

It is worth noting that none of the BSD, ABS, UKIS and BERD contain data on most self-employed people, and therefore it would not be possible to examine the impact of knowledge spillovers from the creative industries on the output of the self-employed.

The preferred choice of data combination would depend on the recipient firms that are most of interest. However, we believe that linking to UKIS rather than BERD is likely to provide the more representative and interpretable sample. While it is theoretically preferred to link the ABS to UKIS in order to be able to control for the recipient firms' level of capital spending, in practice the sample size of firms matched in the two surveys is likely to be prohibitively small, in which case using UKIS matched to the BSD would be the preferred option.

The data requirements for estimating the impact on innovation output are similar (as illustrated in Figure 4). This is because while the outcome of interest now also comes from UKIS, ideally one would control for other firm characteristics using data that are not available in UKIS.

4.3 DATA ON KNOWLEDGE GENERATION BY THE CREATIVE INDUSTRIES

Figures 3 and 4 illustrated that there are three sources that could provide data for the 'external' knowledge of the creative industries. However, there are potential limitations to these data that it is important to consider. First, whether the surveys designed to measure innovation activities and spending are representative of all creative industry activity. Second, whether the questionnaire wording in the surveys capture all knowledge generation by those being surveyed. Third, whether there is sufficient sample size in these surveys for robust analysis.

4.3.1 HOW RESPRESENTATIVE ARE THE INNOVATION SURVEYS

The UKIS is better placed than BERD to be representative of the activity of the creative industries, because BERD only samples from known R&D spenders (and over-represents large R&D spenders). However, the UKIS also has its limitations. In particular:

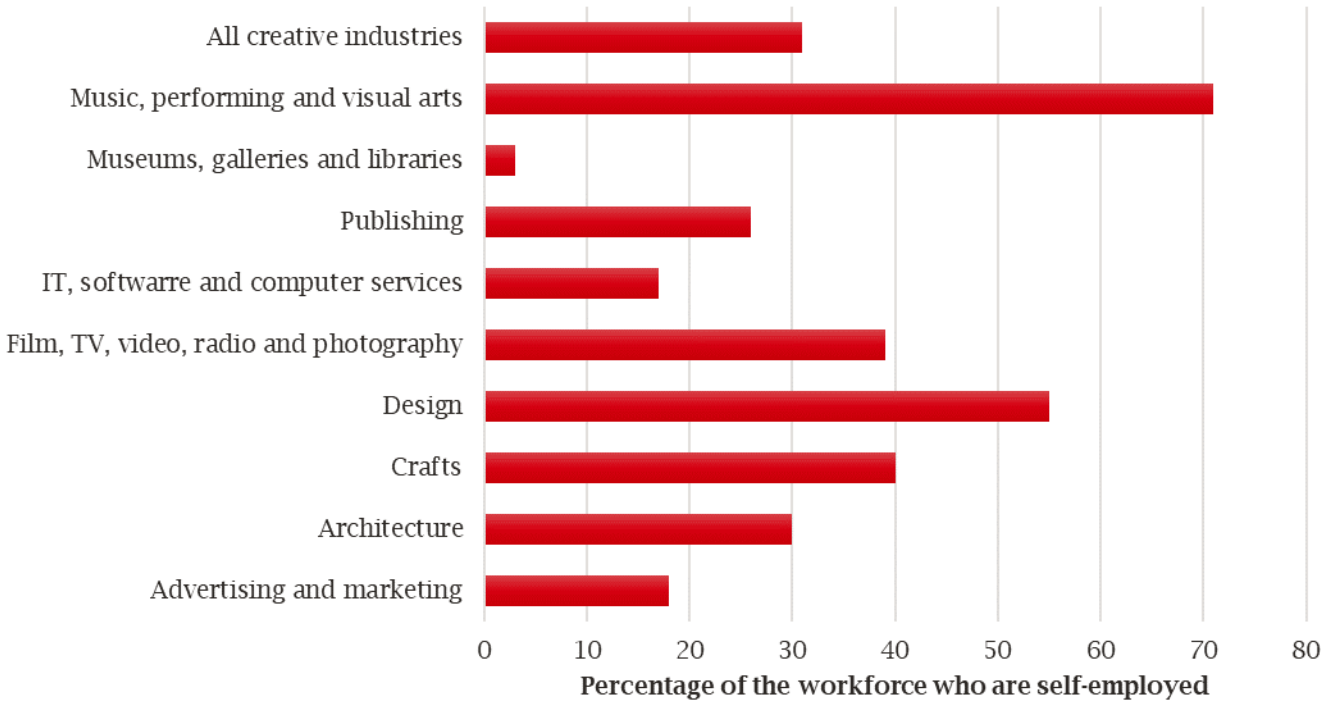
- As with BERD, UKIS does not survey the self-employed. This is potentially problematic, given that 31% of those working in the creative industries were self-employed (PEC, 2020). While the proportion of firms undertaking R&D activities has been shown to be lower for very small firms (Tether 2021), there is almost certainly some innovation generated by the self-employed workforce. Figure 5 summarises data from Giles, Spilsbury and Carey (2020) which shows that the exclusion of the self-employed is more problematic for some subsectors of the creative industries than others: over half of those employed in the 'design' subsector are self-employed, compared to under 20% in the 'IT' subsector.

- UKIS does not survey firms with fewer than 10 employees. In 2019 94% of firms in the creative industries had fewer than 10 employees (compared to 90% of firms across the economy as a whole). Figure 6 shows that this does not vary much across sub-sectors of the creative industries.
- UKIS does not survey firms that are in industries outside categories B-N (according to the SIC2007 classifications). This excludes firms in Section R "Arts, Entertainment and Recreation" – which includes the "Museums, galleries and libraries" sub-sector of the creative industries, and part of the "Music, performing and visual arts" sub-sector.

The bespoke DCMS survey also does not survey the self-employed, but it does survey those with fewer than 10 employees.

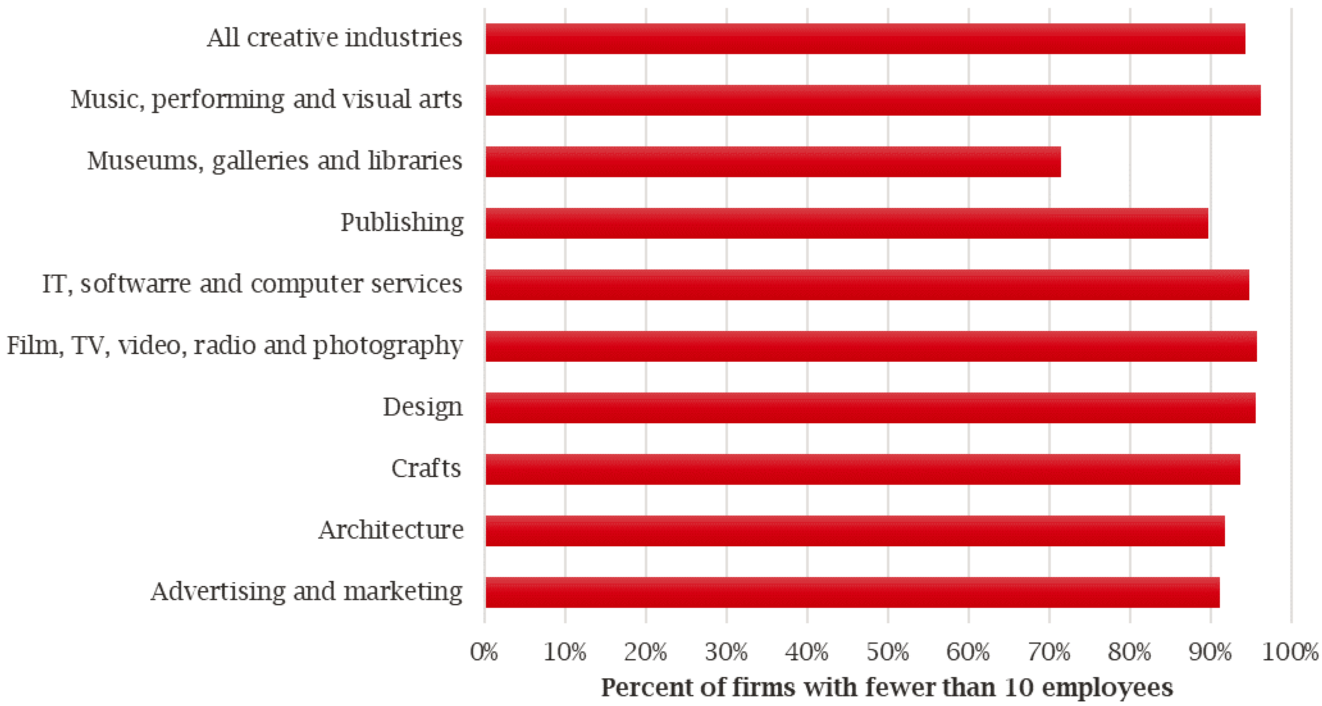
The existing survey data will therefore at best capture the innovation activity of a sub-set of those working in the creative industries – those who are employees, and typically larger firms. If other individuals and firms are assumed to generate no innovation when in fact they do, or conversely if they are assumed to be as innovative as those who are observed in innovation surveys when in fact they are not, then the knowledge stock of the creative industries will be measured with error. This will cause estimates of the knowledge spillovers to be biased downwards.

FIGURE 5 PROPORTION OF THE CREATIVE INDUSTRIES WORKFORCE WHO ARE SELF-EMPLOYED



Source: Giles, Spilsbury and Carey (2020) 'A skills monitor for the Creative Industries'

FIGURE 6 PROPORTION OF CREATIVE INDUSTRIES FIRMS WITH FEWER THAN 10 EMPLOYEES



Source: ONS 'UK Business: Activity, size and location – 2021'

4.3.2 HOW WELL IS KNOWLEDGE GENERATION CAPTURED

Even for those business well represented in survey data, it remains an issue how well captured their innovation activity is. In terms of the questionnaires used by the main innovation surveys:

- BERD: For small employers the survey asks about total in-house R&D spending, total externally commissioned R&D spending, and the number of employees working on R&D.[6] The definition of R&D used is the broad OECD Frascati definition, rather the narrower measure of R&D used by HMRC to assess tax credits. This defines R&D as comprising "comprise creative and systematic work undertaken in order to increase the stock of knowledge – including knowledge of humankind, culture and society – and to devise new applications of available knowledge".[7]

- UKIS: The most recent version of the survey asked about investment "for the purposes of current or future innovation" over the past three years on: internal R&D; acquisition of R&D; machinery, equipment, computer hardware or software; acquisition of existing knowledge; training for

[6] https://www.ons.gov.uk/economy/governmentpublicsectorandtaxes/researchanddevelopmentexpenditure/methodologies/ukbusinessenterpriseresearchanddevelopmentsurveyqmi

[7] OECD (2015) p. 44.

innovative activities; design activities; market introduction of innovations. It also asks about the introduction of new or improved goods, services and processes.[8]

- DCMS: The one-off DCMS survey follows similar definitions of innovation to the UKIS. Firms were asked about their R&D spending, whether they had invested in various equipment or activities for the purposes of development activities, and whether they had introduced new or improved products or processes over the last three years.[9]

These surveys are therefore designed to be relatively broad in the categories of innovation-generating spending or activity that they collect data on. In particular, they are not restricted to the narrower definition of R&D that HMRC uses in tax policy. This is particularly important, as OMB Research (2021) reveals that while 55% of the creative industry firms in the DCMS survey have report having conducted R&D according to the broad Frascati definition, only 14% report having conducted R&D when a narrower definition reflecting that used by HMRC is employed.

However, while the design of the UK innovation surveys recognises a broad range of R&D and innovation generating activities by the creative industries, it is likely that the surveys still underestimate the amount of innovation that is produced by the creative industries. Bakhshi, Breckon and Puttick (2021) highlight that many businesses do not themselves identify their work as R&D. As discussed in section 2, much innovation generation in the creative industries is practice-based rather than the result of specific investment for the purposes of innovation, which makes it hard for individuals themselves to quantify.

This has a similar consequence to the imperfect representativeness of the innovation surveys. Knowledge generation in the creative industries will be measured with error, which risks any estimated spillover effects being biased downwards.

4.3.3 SAMPLE SIZES

In order to estimate the effect of external knowledge on recipient firms' output, the approach detailed in section 3 essentially compares the output of firms with different levels of external knowledge (while controlling for other differences). However, the level of external knowledge will not vary at the firm level – i.e. it will not differ for every recipient firm in the data – if it is matched at a group level. This means that the statistical power to identify a spillover effect depends not just on the number of recipient firms in the data, but also on the number of groups of recipient firms over which the external knowledge differs.

The number of groups for which an external knowledge stock is calculated depends on how groups are defined. For example, they could be based on:

- **Geography**: This would imply that all firms in the same geographical area would benefit the same amount from knowledge creation by the creative industries.
- **Industry**: This would imply that all firms in the same industry would benefit the same amount from knowledge creation by the creative industries, irrespective of where they are physically located.

[8] https://www.ons.gov.uk/surveys/informationforbusinesses/businesssurveys/ukinnovationsurveyukissurveysurveyquestions

[9] See https://www.gov.uk/government/publications/rd-in-the-creative-industries-survey for more details.

- **Geography * Industry**: This allows for recipient firms to differ in their exposure to knowledge generated by the creative industries according to both their industry and location, and is the most theoretically appealing approach.

The more groups there are, the more power the empirical estimation has. This would argue for defining geography and/or industry at very fine levels. But at the same time, it is important that the estimate of the knowledge stock *within* each group is robust. This requires having data on a reasonable number of creative industry firms within each geography, and/or good data on the likely knowledge flow between the creative industries and other industries, in order to calculate robust estimates of the external knowledge stock for each group.

The BERD, UKIS and DCMS data are quite constraining in the definition of geographical groups they would support, as the sample sizes of the creative industries in these surveys is small. The DCMS data, with its sample size of 625 firms, would barely allow the calculation of innovation activities at the regional level (yielding 12 regions, with a minimum sample size within region of just 6).[10] This is not going to adequately capture the true extent of variation in creative industry innovation, which varies significantly within regions.

There are different possible approaches for mapping the knowledge flow between the creative industries and other industries. For example, this could be based on labour turnover or based on supply-chain linkages. The latter approach was taken by Bakhshi, McVittie and Simmie (2008)), who used the UK Input-Output ‘supply and use’ tables that are produced by the ONS to calculate how purchases of creative industry output vary across other industries, and how purchases by the creative industries vary across other industries.[11] However, the ONS input-output tables are quite high level: they divide the UK economy into 105 industries, and many of these will have very limited interaction with the creative industries.

In summary, the existing data on innovation spending and activity in the creative industries do not have sufficient sample size to allow the robust estimation of external knowledge stocks at fine geographical or sub-sector levels. This means that the number of groups of recipient firms for whom the external knowledge measure differs, and the extent of the true variation in external knowledge captured, will both be small. This in turn means that while an augmented production function could be estimated, there is unlikely to be enough power to distinguish whether there is a positive knowledge spillover effect from the creative industries or not.

4.4 SUMMARY

In summary, a production function approach is the technically preferred way of quantifying the impact of knowledge spillovers from the creative industries on the output of other firms. However, in our view existing UK data are not well placed to estimate such effects. As set out above, there are two main limitations. First, some of the knowledge generated by the creative industries is unlikely to be picked up by innovation surveys – because the data do not survey some of the population (the self-employed or small employers) and because those who are surveyed are likely to underestimate their innovation inputs and outputs. This may result in measurement error in the measures of knowledge generation in the creative

[10] Annex table in Tether (2021) reveals that the sample sizes by region in the DCMS survey are East of England 28, East Midlands 24, London 159, North East 20, North West 45, Northern Ireland 6, Scotland 40, South East 136, South West 63, Wales 13, West Midlands 42, Yorkshire & Humber 49.

[11] The ONS Input-Output ‘supply and use’ tables divide the UK economy into 105 industries, and show how the product of each industry is used as an intermediate input by other industries.

industries, which could cause estimated spillovers to be biased downwards. The second limitation arises from the sample sizes of the data available. There is only limited data on innovation by the creative industries, meaning that measures of external knowledge can only be matched to recipient firms for coarse groups – such as those defined based on geographic region and broad industrial category. This will not sufficiently capture variation in the knowledge being generated by the creative industries. While an augmented production function could be estimated, there is unlikely to be enough statistical power to distinguish whether there is a positive knowledge spillover effect from the creative industries or not (particularly once tests are adjusted to take account of the limited variation in external knowledge and the fact that external knowledge is itself estimated).

5 RECOMMENDATIONS

If estimating an augmented production function is the technically preferred method, but current UK data are not sufficient to implement this approach, what can be done to estimate knowledge spillovers from the creative industries? We discuss three broad options. The first (discussed in section 5.1) would yield the most robust estimates but requires new data collection that is costly and time consuming. The second option (discussed in section 5.2) is quicker to implement but has issues of attribution. The third option (discussed in section 5.3) is to directly ask people to identify spillovers, but it may be hard to get reliable data from this approach.

If the DCMS wishes to pursue a quantitative assessment of the spillover benefits of the creative industries, whether from innovation specifically or more generally, then our recommendations are three-fold:

1. We recommend they commission research to examine in detail the correlation between creative industry activity and other firms' output or innovation (option 2). This would yield valuable evidence on possible spillover benefits from the creative industries quickly and at relatively low cost.

2. We feel that the cost of collecting comprehensive new data on innovation activities by creative industry firms (option 1) is prohibitively expensive. However, our research has re-iterated that this is an important deficiency in the current evidence base. Therefore, while it may not be possible to conduct a new large-scale survey, where such data can be more easily collected – for example, as a condition of firms' receiving public funding – we would recommend that this is instigated. Over time this will gradually build a valuable data resource that it may be possible to use in future to examine specifically the impact of innovation by the creative industries.

3. Related, where new government programmes are introduced that affect the creative industries, we recommend that data is collected before, during and after implementation with a view to quantifying the impact of the programme both on treated firms and more widely in the local area.

5.1 OPTION 1: COLLECT ADDITIONAL DATA TO FACILITATE A PRODUCTION FUNCTION APPROACH

The first option is to collect new data so that a production function approach could be estimated. The main requirement would be to collect sufficient data on the innovation activities of creative industries to be able to produce robust estimates of knowledge creation at local levels of geography. This would require a survey with a large sample size: for example, collecting data from 30 firms in each of 173 local areas would require a total sample in excess of 5,000.

In addition, it would be valuable to improve understanding of the links between firms in the creative industries and firms in other industries, and therefore how the size and importance of knowledge flows might be expected to vary for firms in different industries. This could involve trying to produce 'input-output' tables for sub-sectors of the creative industries, or examining whether supply chains vary across the country. However, this is less important than increasing the data available on innovation.

This option would yield the most technically sound and broad-based estimates of the size of knowledge spillovers from the creative industries. However, the new data required would be time consuming and costly to collect - likely in excess of £750,000. Furthermore, while these new data would enable a production function approach to be estimated, it is important to acknowledge that there would still be limitations. First, even with the sample size described, the spillovers from the creative industries on wider economic activity as a whole may be too small to reliably detect. Second, some innovation in the creative industries may be missed if individuals underreport their investments or innovation. This would not be fixed by increasing the sample size of firms surveyed, and there are not obvious improvements that could be made to surveys to fix this underreporting, Third, the collected data may not be representative or smaller employers (depending on who is surveyed). Both these limitations risk biasing estimated spillover benefits downwards. Finally, even with the suggested data it would not be feasible to estimate spillovers *within* the creative industries using this approach, and the ability to focus on particular industries who might receive spillovers may be limited.

We view this option as likely to be prohibitively expensive, however, we provide further additional detail of the data required below.

5.1.1 IMPLEMENTING ADDITIONAL DATA COLLECTION

New data collection could be conducted either through expanding the coverage of an existing survey or by conducting a new bespoke survey.

The existing surveys that could potentially be expanded to sample more creative industry firms are the UK Innovation Survey (UKIS) and the Business Enterprise Research and Development (BERD) which were discussed in Section 4. The main advantage of collecting additional data by expanding an existing survey is that it may be more cost effective, since the infrastructure for these surveys already exists. However, there are two important disadvantages. One is that expanding either UKIS or BERD would require the agreement of ONS, which would take time to negotiate and may not be possible. There would be complications for ONS that would arise from having an altered sample, such as the weights or guidance that would need to be developed to ensure that the data when used as a whole were still representative of all sectors activity. The second is that the new data collection would be constrained by the sampling frame, periodicity and content of the existing survey.

In terms of expanding UKIS, the two main constraints imposed are: (i) UKIS is only conducted every two years, so it could be some time until new data were available; (ii) the sampling frame for UKIS is employers with 10 or more employees and it would be unlikely to be possible to change that for the expanded sample. In terms of expanding BERD, the two main constraints imposed are: (i) only creative industry firms known to be spending on R&D would be sampled, which may miss much innovation activity; (ii) there is only limited data collected by BERD and there is likely to be little scope for expanding that (most firms are sent a short version of the full BERD questionnaire already in order to improve response rates).

Given these pros and cons, in our view additional data collection would be better served by conducting a new survey. This would be more timely, with greater flexibility over sampling frame and survey content. The latter means that the new survey could also be developed to serve multiple purposes, if there are other open questions relating to the creative industries that require new data on a large sample of firms to answer.

For the purposes of quantifying spillovers, the key desirable features of new data collection are:

- **Sample frame**: Ideally the survey would be representative of all those working in the creative industries, not just those working for firms that employ 10 or more people. However, in practice it is likely to be difficult to identify the self-employed working in the creative industries. Firms in the creative industries could be identified from the Inter-Departmental Business Register, based on registered SIC code. This has disadvantages, but alternatives such as identifying business and allocating SIC codes through web scaping are less well developed for this purpose.

- **Sampling methodology**: A key need for the new data collection is widespread geographic coverage with robust sample sizes for individual geographic areas. Ideally the data would also have robust sample sizes for sub-sectors of the creative industries. It would also be advantageous to oversample larger firms, to ensure that they are adequately represented in the data, given that they will be responsible for a large proportion of innovative activity. This would require a disproportionate stratified random sampling approach, with businesses stratified by geography, sector and firm size. Weights would be required to be produced to ensure the resulting measures of innovation were representative for geography-sector groups.

- **Sample size:** A very large sample size would be required to produce robust estimates of innovation for geography-sector groups with geography defined at a fine level (such as Travel-To-Work-area (228 areas), International Territorial Level 3 (173 areas) or local authority districts (374 areas). For example, a sample of 30 firms in each geography-sector group would require a sample size of 46,710 firms if there were 9 sub-sectors of the creative industries separated and geography was ITL3 with all geographies sampled. Even if sub-sectors of the creative industries were not separated, achieving a sample size of 30 firms in each ITL3 area would still require a sample of 5,190 if all areas were sampled. The focus could be restricted to geographies with a minimum concentration of creative industry activity, but a large number of geography-sector groups is necessary to provide sufficient power for statistically identifying spillovers in the main empirical estimation.

- **Periodicity**: A sufficiently large cross-sectional survey would be sufficient for the analysis of spillovers from the creative industries. Repeating the survey over time would increase the sample size for analysis (pooling together two time periods would double the sample size) but would not have other large advantages. The use of panel data methods in the empirical approach for estimating spillovers, will still be constrained by a lack of panel data on recipient firms.

- **Content:** The main objective of additional data collection for the purposes of quantifying knowledge spillovers from creative industries would be to ascertain the level of spending on innovation by creative industry firms. For consistency, and to aid comparability between the creative industries and other sectors, these questions should be modelled on those asked in UKIS. Given the fixed costs involved in conducting such a large survey as that proposed here, it would be worth considering whether there is other data that should be collected alongside that would help to answer other important policy questions relating to the creative industries.

5.2 OPTION 2: USING ACTIVITY AS A PROXY FOR KNOWLEDGE GENERATION

If new data collection is not possible, then one alternative is to attempt to estimate spillovers from creative industry *activity* rather than from creative industry *knowledge generation.*

This approach has two main advantages:

- First, data on creative industry activity is easier to come by than data on innovation generating activities. For example, data on business counts and turnover can be obtained from the Business

Structures Database, data on gross value added can be obtained from the Annual Business Survey and data on employment can be obtained from the Annual Population Survey. Alternatively, web-scraping approaches could be used to construct measures of business counts for the creative industries at relatively low cost. This means that firms could be classified as being in the creative industries using information from their websites rather than the Standard Industrial Classification (SIC) codes held by ONS, and their geographical location can be determined using contact details from their websites rather than company registration details held by the government.

- Second, focussing on creative industry activity would avoid concerns about knowledge generation being underreported in the creative industries because it often arises from everyday problem solving rather than specific investments aimed at producing innovation.

The main difficulty with this approach is attributing causation to any observed correlation. For example, it may be tempting to argue that an observed positive correlation between firms' outcomes and creative industry activity is due to spillovers from the creative industries. However, it is important to try and rule out the presence of unobserved factors, such as drivers of local economic growth, that are causing both creative industry activity and other firms' outputs to increase.

There are a few studies have used variations of this approach in the past. For example, Gutierrez-Posada, Kitsos, Nathan and Nuccio (2021) examine the relationship between the 10-year change in employment in a local area and the 10-year change in the number of jobs in the creative industries. They attempt to attribute causation through an instrumental variables approach, using the historical location of art schools and the location of coal mines as historical instruments. Bakhshi, Lee and Mateos-Garcia (2014) examine the relationship between wages and the clustering of creative industries. Bakhshi, McVittie and Simmie (2008) examine how the innovation activity of firms is associated with how much firms buy from or sell to firms in the creative industries.

Overall, we believe that this approach has merits and, despite the difficulties of truly establishing causation, updated evidence on the correlations between creative industry activity and other firms' outcomes would be valuable. Such research could (and should) be precise about the hypothesis being tested, and the possible spillovers mechanisms being examined. There would be merit in updating the analysis of Bakhshi, McVittie and Simmie (2008) given how commonly that evidence is cited and that it is now over a decade old. The approach taken in that paper, which suggested supply chain interactions as a mechanism for knowledge spillovers, could also potentially be expanded. For example, by examining labour turnover between firms as a possible indicator of knowledge spillovers, or by taking into account geographical differences in the density of creative industry firms. Compared to the new data collection in option 1, implementing option 2 would be considerably cheaper – likely in the region of around £80,000. It could also be conducted relatively quickly, and therefore would yield valuable evidence sooner than if new data were collected.

5.3 OPTION 3: OTHER BESPOKE DATA COLLECTION

A third approach is to collect other bespoke data to examine spillover benefits. There are many ways of doing this.

One method is to conduct a randomised control trial (RCT) – in other words, a policy experiment that is expected to generate knowledge spillovers from a group of firms in the creative industries. If data are collected on the group treated by the experiment and a suitable control group, then a comparison between the two could be used to illustrate the impact of knowledge spillovers.

This approach was used by Bakhshi et al (2013) to evaluate a business support scheme called Creative Credits. These were vouchers that were designed to encourage small and medium sized enterprises to innovate in partnership with creative service provides. By conducting bespoke surveys of firms who were and were not assigned creative credits, 6 and 12 months after the introduction of the scheme, it was possible to causally identify the impact of the encouraged interactions between firms.

Such interventions are expensive, and the findings are often not generalisable away from the specific context of the experiment that is run. This means that it is unlikely to be cost-effective to run an RCT purely with the objective of estimating the size of knowledge spillovers. However, where such policies are being implemented already for other reasons, it would be extremely valuable to introduce or trial policies in a way that allows for the evaluation of their benefits, which could include quantifying the existence of knowledge spillovers. This may involve the collection of data before, during and after the policy is introduced, although the exact timing and nature of the data that should be collected will depend very much on the context in question.

Another method is to collect qualitative evidence that highlights spillover benefits from the creative industries, and several studies in the past have used case studies to this effect.[12]

It is sometimes possible to collect 'quantitative' data that is more qualitative in nature. For example, Tafel Viia et al. (2011) suggested including questions in the EU-wide Community Innovation Survey (CIS) (of which UKIS is the constituent UK survey): *What is the share of new products and services that: (a) are based on the knowledge/invention of CI sector (knowledge spillover) (b) are produced due to the new services and products in CI sector (product spillover) (c) are produced due to the increased demand which is induced by CI sector (demand spillover).* However, we are sceptical how well firms would be able to answer such questions.

Overall, we believe that qualitative evidence is extremely valuable for providing real world, tractable examples of spillovers, but it is difficult to use such data to gauge the prevalence or total value of spillovers across the creative industries.

[12] See, for example, the Independent Review of the Creative Industries by Sir Peter Bazalgette (2017), Frontier Economics (2016), Frontier Economics (2015).

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ANNEX A - TECHNICAL ANNEX

A.1 - THE AUGMENTED PRODUCTION FUNCTION APPROACH

The augmented production function approach follows Griliches (1979) by including in a Cobb-Douglas production function 'knowledge stock' and 'external knowledge stock' in addition to standard labour and capital inputs:

$$y_{it} = AC_{it}^{\alpha}L_{it}^{\beta}K_{it}^{\gamma}S_{it}^{\vartheta}e^{u_{it}} \qquad [1]$$

where y_{it} is the output of firm i at time t, A is a constant, C is physical capital stock, L is labour, K is own knowledge stock and S is the external knowledge stock.

Th production function in [1] can be transformed by taking natural logarithms, and therefore estimated using the linear equation:

$$\ln y_{it} = A + \alpha \ln C_{it} + \beta \ln L_{it} + \gamma \ln K_{it} + \vartheta \ln S_{it} + e^{u_{it}} \qquad [2]$$

The estimate for ϑ is a measure of knowledge spillovers. If $\vartheta > 0$ then there are positive knowledge spillovers – i.e. external knowledge has a positive impact on the recipient firm's output over and above its own inputs of capital, labour and knowledge.

A key complexity with estimating equation [3] is in defining the internal and external 'knowledge stock' (K_{it} and R_{it} respectively). The assumption typically employed is that investment in research and development (or some other measure of investment in innovation generating activity) creates knowledge – and therefore the stock of knowledge is proxied by an accumulation of R&D (or similar) investments over time.

The most common methodology for calculating the accumulated stock of knowledge over time is the 'Perpetual Inventory Method', which assumes that the stock of knowledge evolves over time according to the addition of new investments in knowledge (k_{it} or r_{jt}) and the depreciation of the existing stock of knowledge:

$$K_{it} = (1 - \delta_i)K_{it-1} + k_{it} \quad \text{and} \quad R_{jt} = (1 - \delta_j)R_{jt-1} + r_{jt}$$

Often a depreciation rate of 15% is assumed. In the absence of long-run data on investment spending, it is often assumed that in the long run investment in knowledge grows at a constant (firm-specific) rate (g_i). Then:

$$K_{it} \approx \frac{k_{it}}{\delta_i + g_i} \text{ or } \ln K_{it} \approx \ln k_{it} - \ln(\delta_i - g_i)$$

Under these assumptions the estimating equation [2] becomes

$$\ln y_{it} = B + \alpha \ln C_{it} + \beta \ln L_{it} + \gamma \ln k_{it} + \vartheta \ln S_{it} + e^{u_{it}} \qquad [3]$$

Where output depends on the flow of investment in new knowledge rather than the total stock of knowledge.

The external knowledge stock (S_{it}) available to firm i is the weighted sum of the knowledge stock of other firms:

$$S_{it} = \sum_{j \neq i} w_{ji} R_{jt} \quad [4]$$

Where R_{jt} is the 'knowledge stock' of firm j at time t, and w_{ji} are weights designed to capture the proportional knowledge flows between firm j (the source of the knowledge spillover) and firm i (the receiver of the knowledge spillover). These weights capture the idea that knowledge flows will be more likely, or more impactful, between some firms than others.

Many different approaches to these weights have been taken in the literature. For example:

- Technological proximity. This aims to capture the idea that knowledge generation is more useful to firms that operate using similar technology.
- Product market proximity. This aims to capture the potentially negative spillovers that might occur through rivalry: an external firm may be able to use its knowledge creation to gain market share.
- Supply chain links. This aims to capture the links between companies through the supply chain – either forwards spillovers that flow from suppliers or backward spillovers that flow from buyers.
- Networks. This aims to capture links between collaborators in knowledge generation, such research collaborations between individuals employed in different firms.
- Labour force linkages. This aims to capture the idea that knowledge spillovers might occur through the movement of labour between firms.
- Geographical proximity. This aims to capture the idea that knowledge spillovers are more likely between firms that are geographically closer together.

Sometimes these different approaches are combined in single weight: for example, geographical and supply chain links, such that the external stock of firms that are both geographically close and linked through the supply chain are given more weight than the knowledge stock of firms that are linked through the supply chain but are more geographically dispersed, or the knowledge stock of firms that are geographically close but not connected through the supply chain. Sometimes studies estimate equation [2] or [3] including more than one measure of external knowledge stock to measure the relative strength of different knowledge spillovers.

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