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Infrastructure and manufacturing: their evolving relationship

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Infrastructure and manufacturing: their evolving relationship

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Contents

Executive summary

This paper provides an overview of the evolving relationship between infrastructure and manufacturing in the UK. That relationship is important to understand in order to make the right investments in infrastructure today, bearing in mind the long lags and high costs of infrastructure development. Conversely, changes in infrastructure technology drive changes in manufacturing. The paper addresses four questions:

- What is the "infrastructure problem?" Why is there a need for policy action?
- In what ways is manufacturing dependent on infrastructure? How does this change according to the manufacturing sector? How do changes in the organisation of the manufacturing process affect the demand for infrastructure?
- How do changes in the technology of infrastructure drive changes in manufacturing?
- What does all this mean for public policy?

We addressed the first by reviewing the literature on the "infrastructure investment gap" which estimates a growing disparity between the quantity and quality of infrastructure available and current and future needs. The infrastructure gap is an important matter for government because it affects the international competitiveness of the UK.

We addressed the second question by reviewing some of the economics literature that relates public infrastructure to output and productivity by specifying (and estimating) production and cost functions. We also provided many examples, including two case studies, of airports and satellite systems. We addressed the second and third questions by developing a conceptual framework that has three legs: a categorization of manufacturing from the manufacturing strategy literature that makes it easier to understand how manufacturing has evolved; a distinction from the economics literature between the stock of infrastructure (capital) and the services it generates, and then a typology of infrastructure services that are critical for manufacturing; and a characterization of infrastructure as either satisficing or enabling.

We present two cases that show that the relationship between infrastructure and manufacturing is not only in one direction. While infrastructure through the services it supplies supports manufacturing activity in a wide variety of ways, innovations in infrastructure also stimulate innovations in manufacturing. We go beyond the Keynesian justification for infrastructure – which results in a volume effect -- to the potential of (enabling) infrastructure to create upstream and downstream innovations in manufacturing, even the establishment of whole new industries. The last question relates to policy recommendations. The principal tool used to guide infrastructure investment decisions is cost-benefit analysis (CBA). While CBA may be a useful tool to compare alternative ways of delivering the same service (e.g. travelling between two points) and hence prioritise investment once the services required are fully specified, it is difficult to see how it can help us choose which infrastructure services to prioritise.

This leads us on to our recommendations. There is a considerable number of research case studies of infrastructure use, particularly in the transport sector. We would recommend a detailed review of these studies using the tools in this paper, and recognizing the important differences between infrastructure sectors. Similarly, we recommend that the portfolio of projects in the National Infrastructure Plan be revisited via our proposed approach, especially from the perspective of manufacturing.

1. Introduction

This paper provides an overview of the critical relationship between infrastructure and manufacturing in the UK. This relationship is not new. But it has evolved over time as the nature of both manufacturing and infrastructure has changed. For example, early in the industrial era in the UK the major manufacturing sectors included coal extraction, steel production, and textiles and directly stimulated transformative innovations in infrastructure such as the canals and railways. The technology and organisation of those industries dictated specific energy needs, supply chain connections, and means to markets. Not only are the major industry sectors in the UK different today, but those same sectors are organised differently, meaning that their infrastructure needs also differ. For example, canals have given way to rail and motorways, and an increasing volume of intermediate and final goods is delivered by air. Today we have more sophisticated logistics, with inter-modality aided by containerization and instantaneous communication.

Just as the infrastructure–manufacturing connection has changed from the 19^{th}-century to today, there will be further changes in the future. It is important to anticipate the evolving requirements of manufacturing in the UK in order to make the right investments in infrastructure today, bearing in mind the long lags and high costs of infrastructure development. Conversely, changes in infrastructure technology drive changes in manufacturing. For example, the steam engine allowed manufacturing to be located away from waterwheels and at a larger scale compatible with mass production. Currently, advanced communications facilitate the disintegration of the manufacturing process, allowing design, finance, administration, component manufacturing, and assembly (for example) to be in different locations.

The paper is organised into seven further sections. Section 2 specifies the three motivating questions we seek to address. Section 3 elaborates on the “infrastructure problem” we putatively face. It is important to address that in order to establish a need for policy intervention. Sections 4 and 5 provide definitions for manufacturing and infrastructure that are required to address the questions properly. Section 6 provides a framework to understand the types of interventions that would be appropriate to address the evolving needs of manufacturing in light of changes in the provision of infrastructure. Section 7 contains two case studies – of aerotropolis and satellite systems – that apply the analytic framework we develop. Section 8 provides a summary and suggests direction for policy.

2. Motivating questions

The paper addresses four general sets of questions:

- What is the “infrastructure problem?” Why is there a need for policy action?
- In what ways is manufacturing dependent on infrastructure? How does this change according to the manufacturing sector? How do changes in the organisation of the manufacturing process affect the demand for infrastructure?
- How do changes in the technology of infrastructure drive changes in manufacturing?
- What does all this mean for public policy?

3. The problem

The problem we face is referred to as the “infrastructure investment gap” (World Economic Forum 2012) in the literature and business and popular press. Conceptually, that is the difference between the “capacity” of the infrastructure society needs, and what exists. Understandably, that is not easy to quantify in practice. In terms of supply, it is not just the amount of infrastructure on and in the ground, in physical units (miles of rail and road, flow capacity of pipes, etc.) that matters, but also its quality and resilience. For example, old water mains can lose a high percentage of their flow through leakage, old or poorly maintained power plants may suffer periodic failures, and so on. A related problem is particularly pertinent to this paper: that some types of infrastructure may be in good condition, but are no longer fit for purpose given the demands of manufacturing. The move to containerization required rebuilding of ports, sometimes in different locations. The increased reliance on air freight and business connectivity requires new types of airports. And the increased reliance of society on instantaneous and ubiquitous communications is making traditional communication networks (telephone cables and landlines) obsolete, in favour of satellite and wireless transmission (We elaborate on airports and satellite communication in our case studies in Section 7).

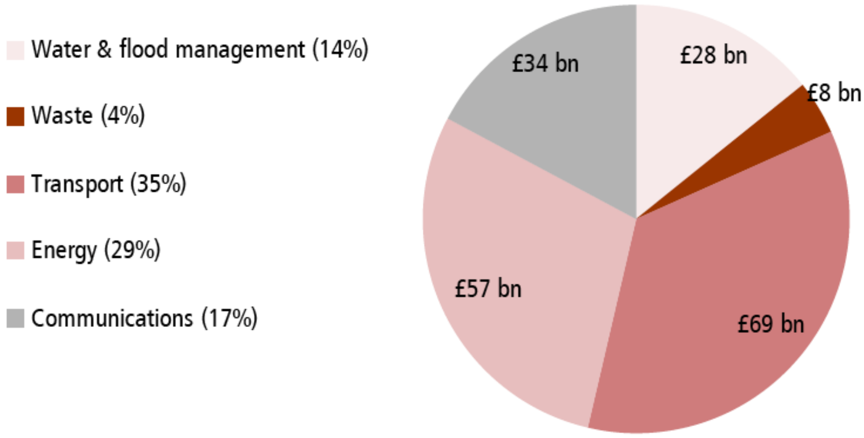
It is also difficult to quantify the demand for infrastructure (and the services it provides).[1] People’s demand depends on patterns of consumption – whether they turn the thermostat down at night, take short showers, etc. And society’s demand depends on shifts in population, rates of deterioration of existing capital, changing technology, and more. Some reports provide trend information on capacity and performance. For example OECD (2012) shows that passenger traffic could double, air freight could triple, and port handling of maritime containers worldwide could quadruple by 2030. Most of the current gateway and corridor infrastructure could not handle even a 50% increase in demand. This estimate indicates either a massive innovation opportunity (smart control systems, etc.) or new construction and installation. But trends in manufacturing could significantly modify these demand estimates. Much container traffic into the UK, for example, is importing goods and empty containers need to be returned. Air traffic for business users in the UK has declined in recent years.

Whilst the various estimates of the “infrastructure investment gap” differ, they are all a large number. In 2009, for example, the UK think tank, Policy Exchange, estimated the need for energy, transport, water, and ICT infrastructure to be £434 billion over the following 11 years (Helm, Wardlaw, and Caldecott, 2009). The Institute of Directors, commenting on that report, claimed it understated the need by at least £66 billion. These estimates are consistent with the gap indicated by Infrastructure UK in its 2010 report, of £40-50 billion per year up to at least 2030 (Infrastructure UK 2010). The OECD estimates that generally countries need to be spending 2.5-3.5% of their GDP annually on telecom, roads, rail, electricity, and water, which at 2011 levels of UK GDP translates into around £73 billion per year (extracted from KPMG (2012)).

[1] In addition, there is a difference between “demand” economically defined and “need” socially defined.

The overall need is the aggregation of gaps in different infrastructure sectors. The Infrastructure UK report shows the distribution of planned investment by sector over just four years, but not the full need:

Chart 1 Planned infrastructure investment 2010/11 – 2014/15 – circa £195 billion (2008/09 prices)



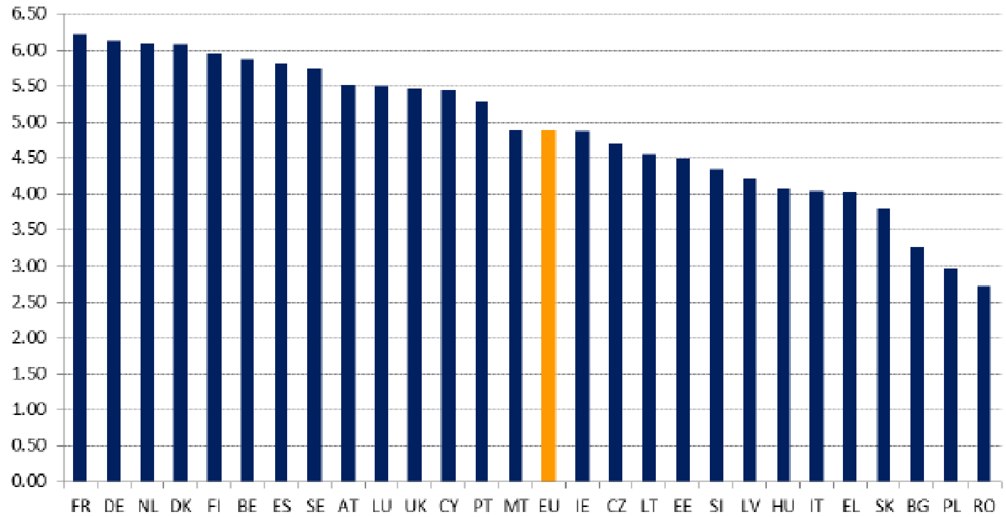
Source: Companies' business plans, regulators, government departments and HM Treasury estimates.

A second way to talk about the infrastructure problem is in terms of key stakeholders' perceptions of the need for and quality of infrastructure. 568 senior executives from businesses of all sizes and sectors across the UK, including investors, providers, and users of infrastructure responded to a recent survey about infrastructure organised by the CBI and KPMG (2012). The responses indicated that (percentage of respondents in parentheses):

- the quality and reliability of transport and digital infrastructure is a significant consideration in investment decisions (>80%)
- digital networks are of growing importance and are a major consideration for the smallest firms.
- energy infrastructure cost is a greater concern than its quality;
- energy (infrastructure) costs are important to investment (90% of manufacturing sector respondents).
- rising energy costs are a concern (95%)
- infrastructure elsewhere in the EU is judged to be better than in the UK (>60%)
- transport infrastructure in the UK is below average by international standards (61%);
- transport infrastructure in the UK is above average by international standards (14%)
- adequate links to domestic markets: 77% in London; 56% in the North West and North East
- the standard of local road networks is declining (e.g. more congestion and lack of investment) (65%)
- High Speed 2 rail link will benefit growth (66%)
- interconnectivity between different transport modes has improved over the last five years (<19%)

Another survey, The EU Global Competitiveness Report 2012-2013, tracks the satisfaction of users of physical infrastructure. The results are presented in Figure 1. Satisfaction is highest in France, closely followed by Germany, the Netherlands, and Denmark. The UK appears to be in a second grouping behind the principal EU economies, but still ahead of the EU as a whole. Unlike surveys of businesses alone, the EU report is based on public consultation and 350 responses from across the social spectrum. The Industrial Performance Scoreboard within the same report indicates that the UK has one of the best-rated business environments in Europe. Among Member States, Germany has the highest overall satisfaction with the quality of infrastructure but has close to an average score on the administrative burden of the regulatory framework.

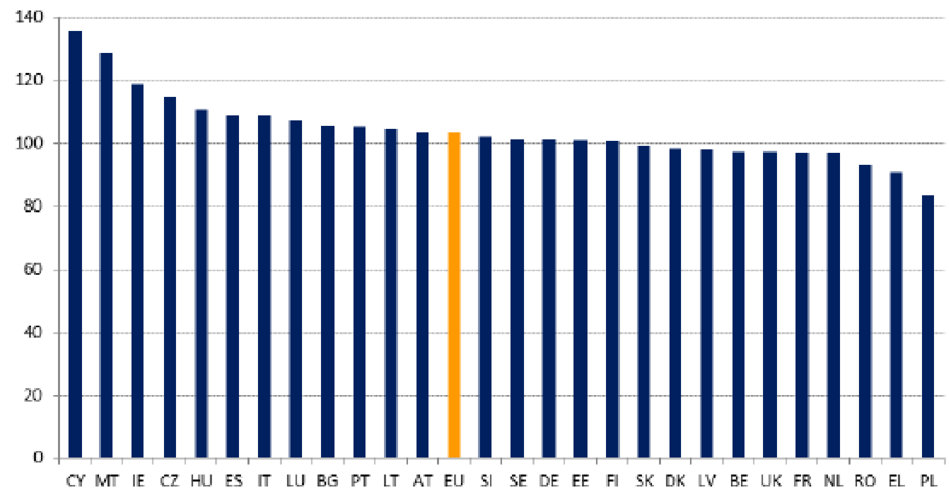
Figure 1. Satisfaction with European Infrastructure 2011



Source: Global Competitiveness Report 2012-2013, World Economic Forum, Commission calculations; refers to rail, road, port and airport infrastructure, 1=underdeveloped / 7=extensive and efficient by international standards.
http://reports.weforum.org/global-competitiveness-report-2012-2013/#

The European Commission has also tracked changes in user satisfaction with infrastructure, as shown in Figure 2. The UK has experienced a small relative fall in satisfaction compared to the EU as a whole, but it is not clear how to interpret that.

Figure 2. Changes in Satisfaction with Infrastructure, 2006-2011



Source: Global Competitiveness Report, Commission calculations; 2006=100

Kadokawa (2011) examines the results of a business location survey and discusses the role of investment in infrastructure, particularly highway infrastructure, in the context of the Japanese manufacturing sector. He confirms that:

- infrastructure plays a significant role in directing the location of plants. After land availability, highways, industrial zones, commuting convenience, and environmental restrictions are almost equally important reasons
- the location of new plants is influenced by the spatial distribution of infrastructure but its importance differs across industries and regions
- transport infrastructure influences the formation of industrial specialization, especially that of light manufacturing industries but is not the dominant factor shaping the industrial specialization of a region.

The BSA Global Cloud Computing Scorecard (2012) measures cloud computing readiness. Broadband access is an underpinning infrastructure feature. The report ranks 24 countries according to seven criteria and provides them with a roadmap for initiatives and policies to promote economic benefit. Harmonisation of the legal and regulatory bases to support cloud computing is emphasised. The 24 countries account for 80% of the global ICT market. The UK is among the global leaders whereas India, China and Brazil rank low on the list of countries. Jurisdictions that provide preferential treatment for domestic suppliers in government procurement, including Brazil, China and Malaysia, rank low, whereas Japan and other members of the WTO Agreement on Government Procurement rank high. Overall Japan ranks highest (83.3) above Australia, Germany, USA, France, Italy and then the UK in joint 6th position (76.6). Brazil is 24th (35.1) China is 21st (47.5) and India 19th (50.0).

The Cisco Global Cloud Index 2011-2016 is an on-going effort to forecast the growth of global data centre and cloud-based IP traffic. The forecast includes trends associated with data centre virtualization and cloud computing. Data traffic information is provided and shows dramatic increases. By 2016 nearly two-thirds of data centre traffic will be cloud traffic. Manufacturing needs are not distinguished. Regional cloud readiness assessment indicated that North America and Western Europe were leading in broadband access (fixed and mobile) and will continue to lead in this category through 2016. On broadband ubiquity, all regions will show measurable improvement in broadband access to their respective populations throughout the forecast period. Asia Pacific leads in the number of subscribers throughout the forecast period due to the region's large population.

3.1 Infrastructure as a component of competitiveness

The top three attributes that make the UK attractive to overseas investors are: quality of life, culture and language; the stable political environment; and technology and infrastructure.[2] This is reinforced by a World Bank report (Iwulska and Quillin 2012) that

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[2] From Ernst & Young's 2012 UK attractiveness survey which is based on an original two step methodology that reflects first, the UK's real attractiveness for foreign direct investors, based on Ernst & Young's European Investment Monitor (EIM) and second, the "perceived" attractiveness of the UK for a representative panel of 500 international decision-makers.
The UK remained the lead destination in Europe for foreign direct investment (FDI) in 2011. It attracted the greatest number of investment projects in Europe. However, Germany has for five years been attracting a higher proportion of FDI and is now at 15%, just 2 percentage points behind the UK. Germany secured a higher share of manufacturing investment projects than the UK for the first time, and attracted twice as many FDI projects as the UK from China.
According to the survey responses the level of demand within the UK and the ability to use the UK as an export base were the first and second most important drivers of FDI decisions, respectively. In contrast,

described Europe as a "lifestyle superpower". This has important implications for how manufacturing might evolve in the longer term, how the diversity of cultures in Europe might encourage innovation including organisational innovation related to manufacturing philosophies, and how these trends then influence the "shape" of manufacturing and the pattern of demand for infrastructure services.

However, in an international comparison, the UK ranked 15th in industrial competitiveness and in five years time is expected to fall to 19th. Germany is the only European country expected to stay in the top 15 over the next five years.

The relative condition of a nation's infrastructure is a component of its economic competitiveness, which is a key policy concern. (The Ernst & Young 2012 UK attractiveness survey ranked physical infrastructure 6th out of 10 categories of competitiveness drivers.) Whilst comparisons of the importance of infrastructure to manufacturing competitiveness are difficult to make across countries because of differences in demographics, industry mix, climate, etc., it appears that Germany and the UK will both lose ground relative to several non-European countries.

The World Economic Forum (WEF) conducts its own annual Executive Opinion Survey as part of its Global Competitiveness Report which aims to capture crucial information not otherwise available on a global scale. The data (see WEF 2012-2013) provide insight into each nation's economic and business environment. The country profiles show that the UK ranked 8th out of 144 countries in 2012-2013 for its overall business environment, which was an improvement on previous years. On infrastructure and technological readiness it ranked 6th and 7th and on innovation and sophistication factors it ranked 9th. In terms of business sophistication and innovation the UK ranked 8th and 10th respectively in 2012-2013). The most problematic factors for doing business are identified but a very small percentage of the survey sample (respond to this question (less than 4%). That caveat notwithstanding, the problematic areas cited for the UK included insufficient capacity to innovate and the inadequate supply of infrastructure.

Table 1 below shows some finer-grained comparisons on various dimensions of infrastructure ("pillar 2" in the WEF report) for selected countries (Australia, China, Germany, India, United Kingdom and United States). The rankings are for the quality of overall infrastructure and infrastructure subsectors (roads, railroad, port, air transport, airline seats, electricity supply, telephone subscriptions). The questions are typically of the format: "How would you assess general infrastructure (e.g., transport, telephony, and energy) in your country? [1 = extremely underdeveloped; 7 = extensive and efficient by international standards].

The UK is ranked 24 out of 144 economies, which is well above average.
In the comparison with Australia, China, Germany, India, and the United States, the United Kingdom is second to Germany on most factors within the infrastructure pillar,

Taking all these surveys into account, the UK's rankings on various dimensions of infrastructure are somewhat mixed. Whether these rankings are good enough is a matter of opinion and political judgment.

Germany's key strengths were seen as its transport infrastructure and logistics, and its telecommunications infrastructure. It is possible that this result is emphasised by the structure of questions in the survey. (Ernst & Young (2012)

Table 1. Perceived Quality of Infrastructure, 2012

Factors	Country	Value	Rank
2nd pillar: Infrastructure			
	Germany	6.36	3
	United Kingdom	6.22	6
	United States	5.81	14
	Australia	5.70	18
	China	4.46	48
	India	3.60	84
2.01 Quality of overall infrastructure,			
	Germany	6.23	9
	United Kingdom	5.63	24
	United States	5.62	25
	Australia	5.24	36
	China	4.28	69
	India	3.81	87
2.03 Quality of railroad infrastructure,			
	Germany	5.73	7
	United Kingdom	5.01	16
	United States	4.83	18
	China	4.60	22
	India	4.44	27
	Australia	4.28	28
2.04 Quality of port infrastructure,			
	Germany	6.04	9
	United Kingdom	5.84	12
	United States	5.58	19
	Australia	5.13	38
	China	4.45	59
	India	3.98	80
2.05 Quality of air transport infrastructure			
	Germany	6.35	7
	United Kingdom	5.96	22
	Australia	5.81	29
	United States	5.79	30
	India	4.71	68
	China	4.53	70
2.A Transport infrastructure			
	Germany	6.24	5
	United Kingdom	5.84	11
	United States	5.75	13
	Australia	5.42	15
	China	4.88	30
	India	4.57	38
2.B Electricity and telephony infrastructure			
	United Kingdom	6.60	4
	Germany	6.48	6
	Australia	5.97	19
	United States	5.87	21
	China	4.04	82
	India	2.63	115

The evidence summarized above provides a strong case for the kind of attention infrastructure has been given in the UK, for example with the creation of Infrastructure UK and the recent appointment of an “infrastructure czar” (Lord Deighton). There is a large infrastructure investment gap, defined by insufficient capacity to meet existing needs and to meet the changing needs of the manufacturing sector. It is important to close that gap in order to maintain the UK’s economic competitiveness. These arguments go further than the traditional macroeconomic (Keynesian) case for infrastructure investment – that it primes the pump of economic growth.

4. Defining "manufacturing"

The Foresight definition of manufacturing is "a system of value-creating activities required to develop, produce and deliver goods and services to customers. Activities may stretch from R&D at one end to recycling at the other." Key in this definition is a process of transforming inputs into a finished product. Governments typically classify manufacturing by their finished product. The UK Office of National Statistics divides manufacturing into the 25 categories shown in Table 2:

Table 2

Office of National Statistics Manufacturing Divisions
Other Mining and Quarrying
Manufacture of Food Products
Manufacture of Beverages
Manufacture of Tobacco Products
Manufacture of Textiles
Manufacture of Wearing Apparel
Manufacture of Leather and Related Products
Manufacture of Wood and of Products of Wood and Cork, except Furniture;
Manufacture of Articles of Straw and Plaiting Materials
Manufacture of Paper and Paper Products
Printing and Reproduction of Recorded Media
Manufacture of Coke and Refined Petroleum Products
Manufacture of Chemicals and Chemical Products
Manufacture of Basic Pharmaceutical Products and Pharmaceutical Preparations
Manufacture of Rubber and Plastic Products
Manufacture of Other Non-Metallic Mineral Products
Manufacture of Basic Metals
Manufacture of Fabricated Metal Products, except Machinery and Equipment
Manufacture of Computer, Electronic and Optical Products
Manufacture of Electrical Equipment
Manufacture of Machinery and Equipment n.e.c
Manufacture of Motor Vehicles, Trailers and Semi-Trailers
Manufacture of Other Transport Equipment
Manufacture of Furniture
Other Manufacturing
Repair and Installation of Machinery and Equipment
Source: UK National Statistics, Publication Hub http://www.statistics.gov.uk/hub/business-energy/production-industries/manufacturing

Similarly, the US Department of Commerce uses the North American Classification System shown in Table 3:

Table 3

North American Industry Classification System
Mining Sectors: 211, Oil and Gas Extraction 212, Mining (Except Oil and Gas) 213, Support Activities for Mining Manufacturing Sectors: 311, Food Manufacturing 312, Beverage and Tobacco Product Manufacturing 313, Textile Mills 314, Textile Product Mills 315, Apparel Manufacturing 316, Leather and Allied Product Manufacturing 321, Wood Product Manufacturing 322, Paper Manufacturing 323, Printing and Related Support Activities 324, Petroleum and Coal Products Manufacturing 325, Chemical Manufacturing 326, Plastics and Rubber Products Manufacturing 327, Nonmetallic Mineral Product Manufacturing 331, Primary Metal Manufacturing 332, Fabricated Metal Product Manufacturing 333, Machinery Manufacturing 334, Computer and Electronic Product Manufacturing 335, Electrical Equipment, Appliance, and Component Manufacturing 336, Transportation Equipment Manufacturing 337, Furniture and Related Product Manufacturing 339, Miscellaneous Manufacturing Source: http://trugroup.com/standardindustrialclassification

In both cases we include mining. In both country cases there is a further breakdown of manufacturing industry subsectors for greater specificity.

Two important points need to be made about this definition of manufacturing. First, whilst these are considered finished products of a particular process, they are also often used as intermediate inputs into other finished products. Computers are inputs into transportation equipment manufacturing, chemicals are used in agricultural production, fabricated metals are used in construction, and so on.

Second, there is a separate classification system for services, and services as well as R&D, are also used in the manufacturing process as intermediate goods.

Tables 1 and 2 present a set of manufacturing sectors that are meant to be stable over time for purposes of statistical consistency. However, the relationship of these sectors to each other, and their use of other “non-manufactured” inputs (services, R&D, etc) is pertinent because they change over time which affects their need for infrastructure.

We can use the manufacturing strategy literature (c.f. Hill, 1993) to present a somewhat different categorization of manufacturing based more on actual manufacturing activity. This distinction is useful later when we relate manufacturing to infrastructure.

- Process industries that use formulas and manufacturing recipes in production, such that the product that emerges cannot be distilled back to its basic components (e.g. food and beverages, paints, drugs)
- Mass manufacturing industries that produce large quantities of a standardized product in a continuous process (household appliances, vehicles, for example)
- Large/small batch industries that produce the product over a series of stages (e.g., inks and paints, bakeries, some shoes)
- One-off manufacturing industries that build one product at a time, often to customised specifications (for example, prototypes or some buildings)
- Extraction industries that remove and separate materials from their original location (mining for example) and provide key inputs for manufacturing processes.

This is a useful taxonomy to describe changes in manufacturing over time. The organisation and technology behind all these types have evolved, changing their need for infrastructure and in response to changes in infrastructure. A case in point is the rapid rise of 3-D printing which has characteristics of both one-off and mass manufacturing industries since the process allows customized products to be produced in large numbers.

5. Defining "infrastructure"

"Infrastructure" refers to long-lived and costly capital assets often with complex design architectures that are required for economic growth and development in the public and private sectors.

The infrastructure sectors referred to in this paper include:

- environmental infrastructure (water, wastewater, solid waste disposal)
- transportation infrastructure (roads, highways, bridges, rail, airports, ports)
- energy infrastructure (generation, transmission and disposal in nuclear, coal, gas, renewables)
- telecommunications infrastructure (fibre-optic, satellite, microwave, and "last-mile" access)
- civic infrastructure (town halls, libraries, hospitals, schools, etc.);
- other significant business-related projects (e.g. science parks, large commercial centres).

In all of these sectors, there are issues of project analysis, planning, construction timing and management, logistics, procurement, financing (including private-public partnerships), and regulation, inter alia. In addition, the study of infrastructure is related to sustainability and economic growth and development. In short, these are complex systems that require integration.

5.1 An economics framework for infrastructure

Economists tend to define infrastructure in terms of the capital asset (stock) that is constructed, and the flow of services that asset is able to generate.

As a capital asset (stock) infrastructure has particular features:

- It is very long-lived, often exceeding its "economic life" (as identified in the initial investment appraisal) and its "design life" (i.e. its physical life specified during the initial design process)
- Although the capital is not consumed, it does deteriorate through use and through exposure to the elements.
- It is non-fungible. It is very difficult to adapt redundant infrastructure assets to new uses, with the exception of some civic infrastructure, and such assets therefore represent considerable sunk costs. They can also be very costly to remove once they become redundant.

Another feature of infrastructure in this context is that it is not consumed directly in the economic process, but supports that economic process through the provision of services which are typically shared with other economic and social processes. It is these services which act as the "intermediary" between infrastructure and manufacturing and act as the economic flow to complement the stock.

One way to characterize the role of infrastructure in manufacturing is as an input of production, a refinement of the standard $Q = f(K, L, G)$, where Q is aggregate private output, L represents the private sector labor force, K is the aggregate non-residential stock of fixed capital, and G is the composite stock of what the pubic finance literature refers to as “public capital.” [3] For cases with disaggregated capital, G can be viewed as a vector, and we have more specific relationships to examine (for example, between output and highways, sewers, public buildings, and so on). The literature generally applies three different estimation approaches, using production, cost, and vector auto-regression (VAR) functions.

Production function approach. This approach can be illustrated best for the case where infrastructure is not disaggregated, as shown in equation (1):

$$Q = F(L, K, G) \qquad (1)$$

Most studies in this framework use an aggregate Cobb-Douglas production function to estimate the relationship between output or total factor productivity growth and public capital (e.g., Aschauer, 1989; Munnell, 1990a, b; Pinnoi, 1994; Holtz-Eakin, 1994; Evans and Karras, 1994; Andrews and Swanson, 1995; Garcia-Milá *et al*., 1996; Vijverberg *et al*., 1997; Ligthart, 2000; Ihori and Kondo, 2001). Some studies use a translog production function (e.g., Andrews and Swanson, 1995; Zegeye, 2000). Some studies also use structural models to account for endogeneity among variables including public infrastructure (e.g., Duffy-Deno and Eberts, 1991; Aschauer, 2001). (More on endogeneity below.)

This approach is attractive because it is relatively simple and straightforward to understand, and employs tried-and-true estimation techniques. However, it does not clearly explain the different roles of various types of infrastructure in the production process. G could be power, water, public buildings, or any other reasonable factor. Moreover, other types of infrastructure that cannot be construed as a factor of production – e.g., garbage collection and sewerage – are ignored, creating a serious omitted variable problem. Another problem with this approach is that it invariably omits factor input prices that affect factor utilization, and can thereby lead to biased estimates of production function coefficients (Haughwout, 1998; Nadiri and Mamuneas, 1998).

Cost function approach. The estimation of production functions has a strong engineering flavour. Economists generally prefer more behavioural models in which something desired (profits) is maximized, or something not desired (costs) is minimized. Of the two, the cost function approach is more popular.[4] Consider, for example, equation (2):

$$C(x_j)=g(Q,P_j,K_j,t) \qquad (2)$$

$C(x_j)$ is the total private cost of purchasing the input quantities x_j at prices p_j, Q is output, t is the (exogenous) state of technical knowledge, and K_j is the public infrastructure capital available to the firm, which affects its costs (Berndt and Hansson, 1992). This cost function is dual to the production function. In these models, inputs and output levels, which are choice variables, are considered endogenous to the firm; prices are market-determined, and therefore exogenous.

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[3] In this context “public capital” and “public infrastructure” are synonymous. See, for example, Winch, Onishi and Schmidt (2012), pp. 11-12.

[4]. For more details on the profit function approach, see Lynde and Richmond (1993), and Vijverberg et al. (1997).

Nadiri and Mamuneas (1998) point out several advantages of the cost function over the production function approach. First, by estimating cost functions we can derive the cost elasticities of output as well as specific effects of infrastructure capital on the demand for private sector input factors. Cost function estimation provides insights into a firm's production structure and performance, including technical change, scale economies, and demand for employment, materials, and private capital stock. Second, similarly, cost function estimation allows direct estimates of the various Allen-Uzawa elasticities, essential for understanding the pattern and degree of substitutability and complementarity among the factors of production. Third, the restrictive condition of a unitary elasticity of substitution among inputs, including infrastructure capital, which is imposed in most production function studies of infrastructure, is easier to relax in cost minimization models (Nadiri and Mamuneas, 1998; Sturm, 1998). Most of the studies employ a flexible cost function specification, such as the translog or the generalized Leontief. [5]

These still have limitations. The public capital stock continues to enter the cost function as an unpaid input of production, even though some studies incorporate information on capacity and utilization rates of infrastructure (Shah, 1992; Conrad and Seitz, 1994; Nadiri and Mamuneas, 1994, 1998). Private costs vary with the utilization rate of infrastructure, γ. It can be expressed in logarithmic form as $c \approx \gamma + g + u$, where g is the level of infrastructure stock and u is the disturbance term (Murphy and Feltenstein, 2001). Since most previous studies do not include γ in their models, it is difficult to figure out the real cost-reduction effects of infrastructure services in the private sector. According to Murphy and Feltenstein (2001), if $\text{cov}(\gamma, g) \neq 0$ in the formula, the estimates of the stock level of infrastructure, g, on private sector costs will be biased and "inconsistent." The flexible functional form that is utilized in many of the cost function models is not without its drawbacks. Sturm (1998) and Moreno *et al*. (2002) point out the tendency toward multicollinearity problems. In short, the covariance matrix of error terms is not diagonal. Sturm (1998) adds that the cost function–based models tend to favour cross sectional estimation over time series, which eliminates the ability to examine adjustment paths.

The VAR approach. The vector autoregression (VAR) approach is more data-oriented than it is theory-based.[6] It uses a Granger-causality test to identify the causal directions between variables (McMillin and Smyth, 1994; Sturm, 1998; Pereira and Flores, 1999). That test is performed by regressing one variable on its own lags, and other variables and their lags. In addition, the approach often utilizes impulse-response and variance decomposition analyses to understand how shocks affect variables over time (Sturm, 1998; Pereira, 2001a). By allowing two-way causality, the VAR approach tends to generate larger economic effects for public capital, than do the other approaches. In addition to the direct effect of public capital on private capital and employment, there are feedback effects from private inputs and outputs (Sturm, 1998). When private output increases, the tax base and tax revenues tend to expand, which spurs public investment.

[5] . Elhance and Lakshmanan (1988), Shah (1992), Berndt and Hansson (1992), Lynde and Richmond (1992), Conrad and Seitz (1994), Nadiri and Mamuneas (1994, 1998), Morrison and Schwartz (1996), Sturm and Kuper, (1996), Vijverberg *et al.* (1997), Murphy and Feltenstein (2001), Moreno *et al*. (2002), and Boscá *et al*. (2002) all use this approach.
[6] . For example, McMillin and Smyth, 1994; Otto and Voss, 1996; Batina, 1998; Pereira and Flores, 1999; Ligthart, 2000; Pereira, 2000, 2001a, 2001b).

And, when private employment falls, public investment is often increased as a counter-cyclical measure (Pereira and Flores, 1999; Pereira, 2000, 2001a).[7]

[7] . Pereira (2000) finds that public investment has a positive effect on private output. At the aggregate level, public investment complements private investment and employment. At the disaggregated level, all five types of public investment are complements of private investment, and, three types of public investment – electric and gas facilities, transit systems, and airfields; education buildings, hospital buildings, and other buildings; and conservation structures, development structures, and civilian equipment – are complements of private employment, while two types of public investment – highways and streets; and sewerage and water supply systems – are substitutes. Batina (1998), Pereira and Fluros (1999), Ligthart (2000), and Pereira (2001a, b) have similar results. McMillin and Smyth (1994) and Otto and Voss (1996) reach different conclusions. They find that energy prices, the inflation rate, and hours of work contribute much more to private output than does public capital. However, they do find complementarity between public and private capital.

6. Relating infrastructure and manufacturing

6.1 An analytic framework

In Section 4 we divided infrastructure into several types which correspond to the entries in the first column of figure 3 below.[8] Those entries are meant to be illustrative – other categorizations could be substituted. We also noted earlier that various infrastructure categories can act as complements to each other. For instance, airports and ports need road and rail connections to function, and there is a considerable amount of convergence between the telecommunications sub-categories. We also explained in Section 5 how economists distinguish between the capital stock and the services it generates. The second column of figure 3 shows one possible set of service types that infrastructure capital can allow. They are presented as gerunds to indicate flow and process:

- Commuting – the transportation of people to their regular workplaces. Superior infrastructure here transports people more quickly and less stressfully and thereby allows manufacturers to draw on more regionally distributed skills and have them arrive at work in a better condition.
- Positioning – the location of particular assets. The classic positioning infrastructure is the lighthouse system, but this has become particularly important with the advent of global positioning systems (GPS) which allow precise locations to be determined quickly and continuously.
- Transporting – the movement of goods either as part of the supply chain into manufacturing or the distribution chain to market.
- Travelling – the movement of people to meet with each other for business purposes, distinguished from commuting. Travelling is also important for a number of leisure-related services which are outside the scope of this report.
- Communicating – interpersonal communications beyond co-presence.
- Networking – the creation of nodes of activity which rely for their success on their position in the network of activity.
- Transmitting – the movement of data.
- Disposing - the handling of waste from manufacturing and the disposal of redundant assets.

These considerations suggest a different way of looking at the issue of infrastructure complementarities discussed by Mokhtarian (2003). Her analysis looks at the complementarities between telecommunications and travelling. In our analysis this approach attempts to compare an infrastructure asset with a service. We would suggest that a more appropriate approach would be to investigate substitutions and complementarities between communicating (our definition is more restricted than Mokhtarian's) and travelling on the one hand, and between transportation infrastructure

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[8] Civic infrastructure is omitted from the framework because it is outside the agreed scope of the analysis. Moreover, civic infrastructure typically supports manufacturing through ensuring a supply of healthy and well-educated employees and customers rather than through the provision of services which are, in effect, inputs to the manufacturing process. Energy generation is excluded because it is also outside the agreed scope of this report. Also, it is not clear whether energy generation should be classified as part of infrastructure or as a manufacturing activity.

and telecommunications infrastructure on the other. One could then hypothesise, for instance, that while one would expect to find considerable substitution between different infrastructure assets providing the same service (road vs. rail; telephone vs. email); one would find little substitutability between assets providing different services unless there was also substitutab ility between the services they provide.

Figure 3. Infrastructure as services

Infrastructure Types	Infrastructure services	Manufacturing types
Transportation •Road •Rail •Airports •Ports •Urban transit •Pipelines	Commuting Positioning Travelling	Process industries
Energy •Transmission •Generation	Transporting	Mass manufacturing
Telecommunications •Telephone •Mobile telephone •Broadband •Mobile broadband (Wi-fi) •Satellite systems	Networking Transmitting	Large/small batch manufacturing
Water •Storage •Distribution	Communicating	One-off manufacturing
Waste •Collection •Disposal	Disposing	Extraction

The final column presents different types of manufacturing, as discussed in Section 4.

6.2 Changes in manufacturing

Some general developments in the organisation of manufacturing have important implications for infrastructure. While the *distribution chains* of manufactured goods have been globalised since the industrial revolution and the days of the UK as the "workshop of the world," and the supply of raw materials has been similarly extended, profound changes in the *supply chains* of manufacturing mean that the supply of intermediate inputs has also become globalised. This has led to much greater attention to the effectiveness of supply chains with particular attention to reliability of timely delivery, and hence much more emphasis upon *transporting*.

A second development is that the design and materials transformation processes in manufacturing have become spatially separated, and the former have also been broken down with greater global distribution of the various phases of design. Indeed some leading manufacturers such as Apple now completely outsource materials processing to China. This appears to have led to much greater demands for *communicating, travelling*, and *transmitting*. The globalisation of the distribution of research and development activity would appear to have had similar effects.

Networking is a particular service provided by infrastructure which has a number of dimensions. Looking at cities from an infrastructure perspective, *networking* is one of the most important services they provide – for instance the financial services sector still relies heavily on inter-personal networking even though this is now extensively complemented by *transmitting*. Cities have also historically been at the centres of infrastructure networks for *travelling* and *transporting* in two ways. First cities have developed around important elements of infrastructure systems such as river crossings and ports; second infrastructure systems have been developed to focus on them. London shows both processes at work. As manufacturing has globalised these *networking* services – often dubbed "connectivity" – have become increasingly important as part of the manufacturing process. Hub airports such as Heathrow – by definition nodes on airline networks – have encouraged the location of manufacturing around them.

6.3 Innovations in infrastructure

Innovations in infrastructure have important implications on how it responds to changes in manufacturing organisation and technology. Infrastructure innovation displays many features of a punctuated equilibrium model of socio-economic change. Continuous improvement within a particular technology such as the gradual improvement in the construction and maintenance of roads over decades is complemented by rapid periods of dramatic change such as the introduction of the railways in the mid-19th century which radically transformed both supply and distribution chains for manufactured products. The systemic nature of infrastructure also means that the innovation process has distinctive features not seen in more self-contained technologies (Hughes 1983) which can slow down the diffusion of technologies.

It is also useful to distinguish between what might be called *satisficing* infrastructure and *enabling* infrastructure in terms of the innovations in services that they support. Satisficing infrastructure is regarded by manufacturers as meeting a threshold level. So long as the infrastructure meets certain requirements (e.g. volume of vehicle movements or bandwidth) then manufacturers tend not to be overly concerned with infrastructure and it does not shape their own innovation processes. *Enabling* infrastructure, on the other hand, provides opportunities for innovation both upstream in the manufacturing of the infrastructure asset and downstream in the supply of new goods and services. For instance, the development of the telegraph was central to the development of the electrical engineering industry and provided whole new ways of rapidly *communicating*; a more contemporary example is the development of global positioning systems which provide the basis for a host of innovations in *positioning* for both consumer and intermediate goods and services.

Our contention is that innovations in the services that infrastructure provides are more rapid and responsive to the needs of manufacturing than those of infrastructure itself. Often, these innovations are made by combining different infrastructure services. A simple example is the combination of roads and global positioning systems which is allowing real-time timetable updates at bus stops, improved dispatch of taxis to customers, and real-time tracking of road freight movements.

7. Illustrative cases

We present two cases– one about airports and the other about satellite systems—to illustrate the evolving relationship between infrastructure and manufacturing. Both cases focus on exploiting infrastructure to benefit manufacturing, but in different ways. Airports are established infrastructure, and represent an excellent example of a *satisficing* infrastructure that is presently under considerable pressure in the UK and where the UK is at a competitive disadvantage. Satellite systems are relatively new infrastructure and represent an excellent example of a contemporary *enabling* infrastructure that is currently stimulating considerable innovation and where the UK has considerable competitive advantage. The airport case focuses on how the basic services supplied by airports – *travelling* and *transporting* – have been considerably enhanced through the addition of networking services. Through the evolving combination of travelling and networking services the whole business model of an airport is changing to fully realise this potential. There are implications for how and where manufacturing can be "connected" both globally and regionally. The value chains and industrial systems of companies engaging with aerotropolis need to be appreciated and this leads to them thinking about business models and the new era of manufacturing.

The other case is more focused technologically and industrially and recognises the potential value and relevance of the *positioning, communicating*, and *transmitting* services provided by satellite systems, which can stimulate innovative new products, as well as the stimulus to innovative manufacturing associated with the manufacture and launch of satellites. The expected growth of these industries and supply chains has been recognised in various studies and the justification for a UK space related industry has been made.

7.1 Aerotropolis type developments

Today airports as infrastructure are intermodal transport nodes that have developed into multifaceted business enterprises. Beyond the airport fence in many regions around the world is a landscape of offices, hotels, warehouses, shopping complexes, and logistics depots. London Heathrow is no exception. Kasarda and Lindsay (2011) demonstrate how airports are shaping urban space in the 21st-century much as highways did in the 20th-century, railways in the 19th-century, and seaports in the 18th-century.

The concept has strong relevance for manufacturing as it is being reconceptualised as a globally dispersed system. When a "survival of the fastest" supply chain philosophy prevails, proximity to airports is valued; they are gateways and conduits for flows of people, materials, and information – i.e*. transporting* and *travelling*. Airports are engines for local and regional economic development, attracting aviation and aviation-orientated activity.

The aerotropolis consists of a core "airport city" at the epicentre of a wider metropolis interconnected by dedicated motorways and high-speed rail links. It is designed to attract time-sensitive goods processing and distribution facilities, especially those involved in shipping high value to weight products, firms dependent on frequent business travel, and other opportunistic economic activity.

The aerotropolis label has been applied flexibly to a diversity of environments, planned and unplanned. At Memphis airport, for example, related employment comprises nearly 20 percent of the non-government workforce of the region and spreads across five zipcodes. By the 1990s the area around Chicago O'Hare had eclipsed the Chicago CBD as a focus for job growth and economic development. In Asia examples include Hong Kong, Singapore, Bangkok, Kuala Lumpur, and Seoul Incheon. Kasarda and Lindsay (2011) list over 100 sites in development and operation worldwide.

An important example of an initiative based on these ideas linked to manufacturing is the proposed Airport City in Manchester. Developments underway at Manchester include a major development of a logistics hub to the south of the airport and Airport City itself to the north. Although there is little development of the actual airport infrastructure, it is intended to use it much more intensively with direct routes to emerging markets such as China. The Airport City (www.airportcity.co.uk) Enterprise Zone will focus on science and technology-based businesses. This investment is complemented by new infrastructure investment in link roads (A555), rail (Northern Hub) and urban transit (Metrolink) infrastructure. It was recently announced that the proposed High Speed 2 will also have a stop at Manchester airport.

It is not just the proximity of the airport that is instrumental. Kasarda and Lindsay attribute successful airport-led development to the nature and scale of airport activity (hubbing potential, passenger-cargo split, air carrier support, etc.), how it fits within the overall pattern of metropolitan development, government support and incentives, regional ground transportation accessibility, the cost of land, and regional policy responses to real estate speculation.

The extent to which business developments around London airports are part of a planned or unplanned aerotropolis, or if they evolved because of other competitive advantages, is an important research question. Our own empirical observation is that the UK upstream oil and gas sector is strongly clustered around Heathrow. The principal sites for engineering and technology development for the oil majors, and the principal first-tier suppliers are very near to the airport (locations include Sunbury, Leatherhead, Reading and Gunnersbury). These locations typically cover the whole of the eastern hemisphere for upstream in terms of technology development, engineering design, and project management. The principal exception to this generalisation is Shell, which is based more traditionally near the upstream extraction sites in Aberdeen (Shell's principal Dutch upstream locations are near Schiphol – Amsterdam and Den Haag). Similar effects local to extraction in the Gulf of Mexico would appear to be behind Houston's predominance for the western hemisphere. Given that there is absolutely no history of oil and gas production in the London area, we hypothesise that this distinctive clustering is a result of the *networking* services provided by Heathrow infrastructure complemented by the M25, rather than "classical" location decisions related to the sites of extraction.

7.2 Satellite systems

The Institute of Directors titled an infrastructure for business report as "Space: Britain's New Infrastructure Frontier" (IoD 2012). The report describes a British success story and sets out how a few regulatory and infrastructure developments, including licensing a spaceport, would help the space sector "lift off." In our view, its development is very analogous to the era of the railways as an *enabling* infrastructure in the mid-19th-century in that it is stimulating a whole host of innovations downstream reliant on the services provided by the infrastructure and stimulating the creation of a whole new manufacturing industry upstream in order to supply the infrastructure.

The development of the space industry upstream and downstream is relevant to telecommunications infrastructure services and resilience worldwide as well as many diverse applications for positioning, *communicating*, and *transmitting* services. It is a complex high technology industry where the UK has major strengths in capability and expertise with large forecast markets. By bridging upstream and downstream markets and technologies there is opportunity to capture economic value and to better position applications industries in the global manufacturing system. Thus this relatively new infrastructure asset is currently at a stage where the UK has been historically in other technologies and industries and offers an opportunity to build new era manufacturing capability. In addition there are important resilience and security aspects that make the infrastructure a critical system for managing and controlling most other physical infrastructure systems.

The Space Innovation and Growth Strategy 2010 to 2030 (SpaceIGS 2010) provides some background information.

With regard to upstream:

- The UK's broad science base for space is second only to the US. The UK is a global leader in software design, systems integration and satellite operations. It manufactures entire payloads for around one-quarter of all large telecommunications satellites and dominates the small satellite market.
- Space is currently worth £5.6 billion a year to the UK economy and supports 68,000 high-skilled jobs. The UK space sector has grown on average by 9% each year. Demand for UK products and services in the space sector has been unaffected by the recession. The global space market is forecast to be worth at least £400 billion by 2030.
- Demand will continue to grow as space-based communications deliver new communicating and transmitting services based on superfast broadband, mobile internet, and high-definition and 3D TV. A 20-fold increase in bandwidth can be expected compared to existing satellites, meeting the *communicating* and *transmitting* needs of rural communities in this country and in overseas markets.
- The EU Galileo global satellite navigation system will provide enhanced satellite navigation signals accurate to a one metre range. This will be important in the development of next generation *positioning* services such as automatic caller location to the emergency services.
- In 20 years, space could offer "internet data centres" in orbit that are not only able to provide a more efficient service for consumers but also significantly reduce carbon emissions within the earth's atmosphere for *transmitting* services.
- Earth observation is another growth area, as demand for security and climate-change monitoring and mitigation services increases.
- To capitalise on the opportunities, the UK space industry has produced a 20 year innovation and growth strategy to capture 10% of the global market, creating 100,000 UK jobs in the process.
- UK manufacturing companies are working on next generation technologies, like small-satellite sensors and platforms for earth observation data, technologies for 'single stage to orbit' space planes, developments based around autonomous avionics and composite structures, to reduce the cost and risk of launching satellites.

With regard to downstream:

- Many applications for satellite infrastructure are currently available or under development and are becoming increasingly cost-effective. This is leading to a whole new set of *transmitting* services for innovations such as smart infrastructure and domestic smart services.
- *Communicating* services are also becoming much more geographically widespread in remote areas and at sea (Inmarsat) thanks to satellite systems enhancing safety and providing opportunities for improved economic and social integration. The Global Positioning System (GPS) is currently the most widely used and best known example of GNSS (Global Navigation Satellite System). These can provide a whole host of positioning services in transport networks, particularly road and rail, including collision avoidance, smoother traffic management, fuel efficiency, consignment tracking, and reduced delays. The possibility also opens up of automation of personal road passenger vehicles.

Links between upstream and downstream markets are beneficial to capture value. Space technology applications can be envisaged in insurance, finance, health and agriculture with manufacturing requirements at device- as well as systems- and infrastructure-levels. Thus, satellite systems as telecommunications infrastructure display many important features of our argument:

- They are currently enabling infrastructures which stimulate innovation across a wide variety of sectors by providing services such as positioning, communicating, and transmitting.
- They also stimulate manufacturing demand – in this case science-led high technology demand.

The industry as an infrastructure supplier sector has a potential impact on the intangible "brand" image of UK manufacturing combining knowledge industries and complex high-tech manufacturing organisation in both niche and consumer markets. It fits the criteria indicative of the new industrial revolution (Marsh 2012) both in its upstream stimulus to high tech manufacturing and its downstream enabling of a wide variety of innovations.

7.3 Satisficing and enabling infrastructure

We have classified airports and the linked aerotropolis as satisficing and satellite systems as enabling. Why? For us, the important feature of an enabling infrastructure is that it has both upstream and downstream effects. Some infrastructure systems – particularly in their early years - both enable the provision of a whole new set of services to manufacturing and stimulate significant innovation in manufacturing to the extent of the establishment of whole new industries. Thus the impact of the railways on *transporting* and *travelling* services was profound and much more than a substitution effect for horse-drawn vehicles on roads and canals, but it also stimulated innovations in heavy machine building and the entire rolling stock manufacturing industry. This is distinct from the Keynesian multiplier effect on manufacturing from infrastructure investment which provides volume and not necessarily innovation. The telegraph is another example of a 19th-century enabling innovation. Satellite systems appear to have the same enabling effects today. Implicit in this argument is the life-cycle of infrastructure assets from enabling to satisficing once the initial period of investment is past.

We have defined airports as satisficing infrastructure assets because they do not have the same upstream effect on stimulating manufacturing innovation and providing radically enhanced or even wholly new services downstream. While the development of airports has stimulated innovations in aircraft manufacture such as the need for quieter engines, this does not amount to the radical impacts of the railway, the telegraph, and the satellite for manufacturing. Similarly the development of the motorways stimulated innovation in the car industry to produce vehicles capable of cruising at sustained high speed, but that did not reshape the car industry. In both cases the downstream services were improved and new opportunities were provided (e.g. in logistics for *transporting*) but not radically reshaped. The key policy issue with satisficing assets is typically capacity, while with enabling assets it is technology. Satisficing assets also often have the character of public goods as defined by economists (see Section 5 above) while enabling assets can be financed by generating new income streams.

8. Conclusions and implications for policy

In Section 2 we posed four questions:

- What is the "infrastructure problem?" Why is there a need for policy action?
- In what ways is manufacturing dependent on infrastructure? How does this change according to the manufacturing sector? How do changes in the organisation of the manufacturing process affect the demand for infrastructure?
- How do changes in the technology of infrastructure drive changes in manufacturing?
- What does all this mean for public policy?

We addressed the first by reviewing the literature on the "infrastructure investment gap" which estimates a growing disparity between the quantity and quality of infrastructure available and current and future needs. The gap reflects under-maintenance, and thus deterioration of service levels. But it also reflects obsolescence – or the lack of fit between the type of infrastructure available and the needs of society. In the case of manufacturing, changes in the organisation of production, the emergence of new sectors, etc. require different types of infrastructure than exists. The infrastructure gap is an important matter for government because it affects the international competitiveness of the UK.

We addressed the second question in several ways. We reviewed some of the economics literature that relates public infrastructure to output and productivity by specifying (and estimating) production and cost functions. The theoretical basis of that literature is richer than the empirics due to the complex nature of the specifications and the paucity of appropriate quality data. We also provided many examples, including two case studies, of airports and satellite systems.

We addressed the second and third questions by developing a conceptual framework that has three legs: a categorization of manufacturing from the manufacturing strategy literature that makes it easier to understand how manufacturing has evolved; a distinction from the economics literature between the stock of infrastructure (capital) and the services it generates, and then a typology of infrastructure services that are critical for manufacturing; and a characterization of infrastructure as either satisficing or enabling. Satisficing infrastructures, as the name implies, are principally about supporting manufacturing and other economic and social activities through the provision of valued services. Enabling infrastructures have a much more radical effect in providing wholly new classes of services and stimulating radical innovations in manufacturing – electricity generation and distribution is another example here. Over time, such enablers tend to become satisificers as manufacturing comes to depend on the services provided and innovation slows to a more incremental mode.

The cases we provide in Section 7 show that the relationship between infrastructure and manufacturing is not only in one direction. While infrastructure through the services it supplies supports manufacturing activity in a wide variety of ways, innovations in infrastructure also stimulate innovations in manufacturing. We go beyond the Keynesian justification for infrastructure – which results in a volume effect -- to the potential of (enabling) infrastructure to create upstream and downstream innovations in manufacturing, even the establishment of whole new industries.

This brings us to the last question – about the implications for policy. The brief from the Government Office for Science Foresight team was to provide an analysis which would help prioritise infrastructure investments, and thus contribute to the UK's competitiveness. The principal tool used to evaluate the efficiency (net social welfare) of public investment in infrastructure projects is cost-benefit analysis (CBA). There is a large literature on CBA that argues its strengths and weaknesses. One recent study by Vickerman (2008) notes that a significant weakness of CBA is its limited definition of "benefits." For example, CBA does not take into account the stimulus effect on manufacturing of infrastructure investment, particularly in terms of its inducement of innovation. While BCA may be a useful tool to compare alternative ways of delivering the same service (e.g. travelling between two points) and hence prioritise investment once the services required are fully specified, it is difficult to see how it can help us choose which infrastructure services to prioritise.

The core intellectual problem here may be the absence of a common discipline of infrastructure economics and management. Research and policy is presently balkanised into separate areas of transportation, energy, telecommunications and so on.

This leads us on to our first recommendation. There are a considerable number of research case studies of infrastructure use, particularly in the transport sector. We would recommend a detailed review of these studies through the lens we have proposed here. This would allow our conceptual framework to be tested to evaluate its robustness. It would also allow the identification of interesting leads for further enquiry.

Our second recommendation is that the portfolio of projects in the National Infrastructure Plan be reviewed through the lens proposed in figure 3 from the perspective of manufacturing. Various commentators have suggested that it is a shopping list rather than a strategy, but this perception is, in our analysis, a function of the difficulties of prioritising infrastructure investment due to the limitations of the present investment appraisal toolkit. A currently pressing example of why this is important is around the evaluation of airport strategy in the south east. In our analysis, a number of manufacturing (broadly defined) firms have been attracted to the area around Heathrow by; above all, it's excellent *networking* services. While London's principal airport with its *travelling* and *transporting* services could feasibly be moved elsewhere companies that have made location decisions based on its networking services would be left behind, together with their highly skilled employees. In their decisions to relocate they might well decide to move abroad (e.g. to the Randstad in the case of oil and gas) as this will provide deeper networking and other complementarities than the Thames estuary area.

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