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Standards, Learning and Growth in Britain, 1901-2009*

Christopher Spencer[†] Paul Temple[‡]

Abstract

This paper considers the model of voluntary, consensus based standardization as developed through the British Standards Institution (BSI) and its contribution to learning and productivity growth. It discusses the significant role played by professional engineers in the model's introduction, its extension at home, and imitation overseas. It is argued that by 1931 the BSI catalogue of standards represented a considerable stock of codified knowledge whose growth reflected underlying aggregate technological opportunities, assisting in their transformation into technological advance. To help validate this claim we incorporate a measure of the size of the BSI catalogue of standards into an econometric model of aggregate productivity growth in Britain. We find that the growth of the standards catalogue is associated with a substantial proportion of labour productivity growth over the period 1931-2009. Estimates relating to the short-run dynamics involved are consistent with the idea that there are causal linkages running from standards to growth. When interpreting our findings, it is argued that the overall weight of historical evidence points to standardization - coordinated through the BSI - as providing an important path of learning for the British economy over the period considered.

Key Words: standards, technological change, productivity.

JEL Classification: N1, N8, O11, O33, O47, L52, C22.

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There is now an extensive literature linking standardization - the creation and use of various kinds of industrial norm - with economic growth. The literature has addressed both the economic functions of standards, as well as the processes through which they are created. This paper focuses on the latter issue, examining the role of one organization, the British Standards Institution (henceforth BSI), through which standards are developed through committee deliberation and consensus among the various industrial stakeholders. Using the historical record, we argue that the development of such standards constitutes an important and distinctive mechanism for 'collective learning' in the British economy. Its relevance for productivity growth is assessed by considering an econometric model which complements the qualitative analysis.

The origins of the BSI are to be found within the professional engineering community which, operating through the Institution of Civil Engineers (ICE), established the Engineering Standards Committee (ESC) in 1901. This committee played an important role in coordinating a response by British business to international competitive challenges, especially those from the US and Germany. It is argued that the external economies of scale resulting from the Committee's work could - at least partially - replicate the alternative paths of learning made possible by the frequently larger scale and greater vertical integration of US enterprise, in which many of the benefits of standards could be internalised. We consider the development of the Committee as a model for inter-company coordination, how the committee was established at a national level, and how it was imitated elsewhere in Europe, most notably in Germany, where standard setting has provided an important example of what has been described as 'co-operative capitalism'.¹ To consider further the role of the BSI, the paper discusses the merits of using the number of documents in the BSI catalogue as a measure of institutional output, which represents a broad and significant class of technological opportunities. This indicator allows us to supplement the foregoing qualitative analysis with a quantitative one that focuses on the econometric relationship between standards and UK productivity growth between 1931 and 2009. A statistically significant relationship between productivity growth and our measure of the knowledge generated by the BSI through its Standardization programme is found. This is taken as evidence as to the relevance of this mechanism for learning.

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¹ Chandler, *Scale and Scope*, pp. 393-587.

The paper proceeds as follows: the next section provides a brief résumé of the economics of standards and how the process of standardization links to the idea of learning. Section III considers the origins of the BSI in the creation of the ESC, while section four discusses the evolution the committee structure up to 1931, when the institution (by now the British Engineering Standard Association (BESA)) became the BSI. We argue that this event establishes a suitable starting point for the statistical analysis in section V, where the growth of the BSI standards ‘catalogue’ and its variation over several decades is discussed. In section VI, this variable is used to augment an estimated conventional production function; standards are found to account for a sizeable portion of economic growth over the period 1931-2009. The final section concludes.

II

In many historical contexts, the use of standards – specifications for products or processes created in order to achieve greater consistency - have underpinned learning processes and consequential productivity growth. Learning associated with standardization and process innovation was central to the industrial revolution and the factory system in particular, but as Mokyr has stated ‘standardization of both output and input may well be the most underrated technological development of the Industrial Revolution.’² As a means of capturing the benefits from standardization at the level of the plant or the firm, a strategy of standardization was taken to extreme lengths by Henry Ford in the early 20th century, where standardization was the driver of an immense raft of innovations.³ But history can also furnish us with examples where the learning associated with standardization is not captured at the level of any individual factory or firm, but through inter-firm collaboration.

In the context of standardization through collaboration, there are several questions for historical enquiry. One is the nature of the linkage to economic outcomes – competition and productivity growth in particular. Another concerns the coordinating mechanism which ensures not only that collaboration results in agreement, but also that the standards created are widely adopted. This section considers both in turn.

Standardization provides a variety of economic functions; these include a reduction of variety, the provision of compatibility, and the achievement of a minimum level of quality

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² Mokyr, *Enlightened*, p. 343.

³ Hounshell, *American System*, pp. 217-61.

(which may be useful for regulatory purposes). However when standardization takes the form of a written document, it also provides codified information regarding non-product technology – i.e., for ‘interface protocols, measurement and test methods, evaluated science and engineering test methods, and so on’⁴ – which thereby support the other functions of standards. The aggregate of such codified information creates what Tassey describes as a public good intensive ‘infratechnology’, promoting profitable learning through the creation and deployment of proprietary technologies.⁵

A large part of the economic analysis of standards has focussed on the variety reducing function of standards, where productivity growth is achieved by realising economies of scale. Here, a literature relating standardization processes to industrial life-cycles exists, characterised by the transition from a phase of product innovation in which alternative designs and specifications compete, to one of standardization based on the emergence of a ‘dominant design’.⁶ This functions as the point of reference for standardization in the form of specifications for certain ‘core’ product characteristics around which buyer preferences cohere.⁷ At such a point, price competition may begin to dominate and firm success now centres on achieving economies of scale by making dedicated sunk-cost investments in both equipment and economic relationships (for instance, between employer and employee or between firms). This process may also allow for the substitution of unskilled for skilled labour.⁸ In this case greater competition limits the expected profitability of skilled-labour intensive R&D projects, although it may also encourage incumbent firms to innovate in a more radical way – and ‘escape competition’.⁹

Although it is natural to think of standardization as promoting productivity growth by reducing variety and promoting economies of scale through process innovation, standardization may have quite opposite effects. For example, widely understood ways of measuring product characteristics allow for a more efficient user-producer interface –

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⁴ Tassey, ‘Roles’, p. 161.

⁵ Tassey, ‘Underinvestment’, pp. 91-2, especially figure 1.

⁶ The concept is usually attributed to Abernathy and Utterback, ‘Patterns’.

⁷ An exposition of the general principle can be founded in Geroski, *Evolution of New Markets*. On core characteristics see pp. 80-5.

⁸ See the recent model of Acemoglu *et al.*, ‘Competing Engines of Growth’, in which firms are classified as research intensive ‘innovators’ or as ‘standardizers’. Here, standardisation - acting through the entry of the latter type - provides an ‘engine of growth’ in its own right in which one type of learning is replaced by another.

⁹ Aghion and Howitt, ‘Growth’, section 4.

promoting product innovation and providing a channel for productivity growth in ways suggested *inter alia* by versions of endogenous growth theory in which increased up-stream variety generates productivity advance downstream.¹⁰

The user-producer interface is also at the heart of another literature which has focused on inter-operability and compatibility and their role in creating network externalities.¹¹ This alternative emphasis has partly reflected the importance of compatibility standards for the modern development of information and communication technologies (ICT), but famous historical case studies have featured typewriters and the QWERTY keyboard,¹² and the adoption of standard railway gauges in which railway companies sharing the same gauge could 'much more easily exchange traffic, resulting in lower costs, improved service, and greater profits.'¹³ Such examples suggest that standardization is subject to historically contingent 'lock-in' with the potential for sub-optimal technologies being chosen as the market share of an early technology/standard trumps the characteristics of the technology itself.¹⁴ The economic analysis of these types of standards has emphasized the relevance of strategic behaviour for outcomes, with significant distinctions between a 'standards battle' - where distributional issues are paramount and the prize from establishing a proprietary standard may result in a struggle between relatively evenly matched contenders - and a 'battle of the sexes' problem where individual firm preferences are less important and the major problem is one of coordination.¹⁵

The resolution of such coordination issues in standardization arguably became more important in the context of the newer technologies and industries associated with the so-

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¹⁰ The standard reference is to Romer, 'Endogenous Growth', but in an earlier article Ethier, 'Increasing Returns', employs an essentially similar idea to build on Adam Smith's pronouncements about the importance of the size of the market. For evidence related to the generation of intra-industry trade, see Choudhary *et al.*, 'Taking the Measure'.

¹¹ Early examples in this literature are Farrell and Saloner, 'Standardisation', and Katz and Shapiro, 'Network externalities'.

¹² David, 'QWERTY', speaks of 'system scale economies' rather than 'network externalities' to describe the impact of externalities on the choices of both typewriter manufacturers and typists.

¹³ Puffert, 'Path Dependence', p. 283.

¹⁴ The potential technological superiority of rival technologies has sometimes been challenged. In the famous QWERTY case (David, 'QWERTY'), the idea that the rival Dvorak Simplified Keyboard was superior has been challenged by Liebowitz and Margolis, 'Fable of the Keys'.

¹⁵ A discussion of both these two cases can be found in Besen and Farrell, 'Choosing How to Compete', pp. 122-6.

called 'Second Industrial Revolution' (c1870-1914)¹⁶ in which the potential scale economies became significant in the 'newer' industries – including steel, chemicals, and transport equipment. A central contribution of Alfred Chandler in this regard was to emphasize the importance of learning processes at the firm level in the realisation of these economies, through the coordination of production with upstream flows of inputs as well as forward into distribution, with the latter allowing for high levels of 'stock-turn'.¹⁷ In the new technological systems – in railways, telegraph, and electricity - similar learning processes at firm level were complemented to a greater extent by the need for scientific knowledge¹⁸ but they also required significantly greater amounts of cross-firm and cross-industry coordination for success. But the necessity of the 'Chandlerian corporation' as the unique mechanism for seizing the new economic opportunities has not gone unchallenged, and recent historical analysis now recognises other mechanisms besides markets and hierarchies for coordinating transactions across firms whenever informational asymmetries exist, as pointed out by Lamoreaux *et al.*¹⁹ In the specific context of innovation, Wright has argued that the US developed considerable networks of "collective learning" beyond the boundaries of sponsoring firms' operating nationally rather than simply through the familiar localised industrial district.²⁰ He suggests that both 'invisible colleges'²¹ of skilled mechanics and later the more visible ones of professional engineering associations established norms favouring open information exchange. Examples of the latter include the role of professional bodies in promoting standardization of user-producer interaction in the US steel industry,²² and in the cooperation achieved by engineering professionals in railroads.²³ Mowery and Rosenberg have stressed the more general significance of professional bodies such as the American Society for Testing Materials (ASTM) in establishing the technological

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¹⁶ The dates are those suggested by von Tunzelmann, 'Historical Coevolution', p. 371.

¹⁷ That is, gains in speed rather than pure size. See Chandler, *Visible hand*, p. 236.

¹⁸ Mowery, 'Plus ça change'.

¹⁹ See Lamoreaux *et al.*, 'Beyond Markets and Hierarchies', p. 7; these authors point to the use of standards developed by the Chicago Board of Trade in the adaptation of farming to the potential of the new transport networks, in which individual farm output was no longer identifiable (pp. 22-3).

²⁰ Wright, 'Can a Nation Learn?' p. 297.

²¹ *Ibid.*, p. 296.

²² See Misa, *A nation of steel*; chapter 2 deals with the use of steel construction and the collaboration of architects and steel-makers in Chicago.

²³ Usselman, 'Patents'.

infrastructure for the second industrial revolution, through which standards formed an important mediating link between science and learning at the level of the individual firm.²⁴

In other economies alternative mechanisms can be found. For example, the leadership of Germany in some of the industries of the Second Industrial Revolution and considerable catch-up in others was achieved despite considerably lower plant and establishment size than in the US - or even France or Britain as shown by Kinghorn and Nye.²⁵ These authors hypothesise that German organizational forms (most notably the cartel) were able to substitute effectively for the much larger scale managerial hierarchies observed in the US. In the next section we consider inter-company coordination in the case of Britain, and the role of professional engineers in establishing a model for voluntary consensus standardization which served as the basis for a national institution – not restricted to any particular industrial sector - and which was eventually widely emulated elsewhere in Europe.

III

The increasing challenge from international competition for British industry in the late Victorian era, from both the US and continental Europe, provides the immediate context for the creation of a standards setting body which eventually evolved into a genuine, and possibly the first, 'national' standards setting agency. This section situates this evolution within the context of the substantial and long-running debate concerning Britain's relative industrial decline.²⁶ More recent contributions have emphasized the fact that much technological advance, especially in the newer industries, was now taking place overseas, while differences in relative factor prices, especially in comparison with the US, constrained the extent to which that advance could be directly imitated – at least without local innovation and refinement at the very minimum - as argued by Broadberry.²⁷

Although there is no completely consistent pattern across industries, factors which are usually acknowledged to have favoured more rapid gains from scale economies

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²⁴ Mowery and Rosenberg, *Technology*, chapter 2, especially pp. 46-52.

²⁵ Kinghorn and Nye, 'Scale of Production'.

²⁶ See, for instance, McCloskey, *Essays on a Mature Economy*, and Foreman-Peck, *New Perspectives*.

²⁷ Broadberry distinguishes between 'mass production' and 'craft' systems which can coexist (within limits), with either capable of being the more technologically progressive, despite a persistent productivity advantage in the former ('Technological Leadership', p. 292).

achieved via standardization in the US included the widespread diffusion of the American system of manufacture in combination with more homogeneous consumer tastes based upon a more equal distribution of income.²⁸ Where inter-firm collaboration was important we have already noted the role of a range of professional bodies. The professional engineer was to prove important in the case of Britain as well, but here we need to reference the apparently greater role of the independent consulting engineer and their contribution to 'excessive' variety and short production runs. The engineer was also arguably central to variety proliferation in construction projects, and hence in the demand for constructional iron and steel. In this context, one leading engineer of the time described in 1909 how in the absence of any standard list of sections, engineers and architects 'designed odd sections, or selected sections which could only be obtained at a single rolling-mill, and then found themselves exposed to difficulty and delay in getting delivery'.²⁹ Moreover both the US and Germany had generally adopted 'standard lists' of rolled sections and it was 'known that numerous orders had been refused by American steel-makers because the sections required differed from American standard sections'.³⁰

But the prominence of the senior consulting engineer in construction proved also to be the source of a credible competitive response, coordinated through the auspices of the ICE, whose membership spanned the various engineering disciplines.³¹ The first document claiming recognition as a 'British' standard was the output of a specially constituted committee of the ICE – the ESC – in 1903.³² The ESC's establishment was the result of the motion to the ICE Council by the prominent civil engineer Sir John Wolfe-Barry in 1901.³³ The immediate case of concern – prompted by the British Iron Trades Association – was in the production of rolled steel – a major input into growing industries such as shipbuilding,

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²⁸ This argument can be traced originally to Saul, 'The market'; the significance of the consulting engineer in sustaining excessive diversity has been picked up (for example) by Landes, *Unbound Prometheus*, p. 315, and Mowery and Rosenberg, *Technology*, p. 108.

²⁹ Unwin, 'Standardisation and its influence', p. 101.

³⁰ *Ibid.*, p. 101.

³¹ Founded in 1818, it had received a Royal Charter in 1828 and possessed the largest membership among engineering institutions up to World War I. By the 1820s it had established itself as a body where, 'the reading, discussion, and publication of papers formed the principal activity, which occurred within an intricate hierarchy from associate or junior membership to full membership. .... [which] virtually all senior engineers found ...necessary' (Buchanan, 'Institutional Proliferation', pp. 45-6). As far back as 1841, it was through the ICE that Whitworth announced the eponymous screw thread. By 1860, 'the "Whitworth thread"' had been 'adopted throughout the country' (Roe, *Tool builders*, p. 102).

³² McWilliam, 'The first British Standards', p. 268.

³³ Woodward, *Story of Standards*, p. 8.

railways, tramways and bridge-building.³⁴ For rolled steel shapes and sections, increasing international competition meant that cost reducing strategies were paramount, and attention was inevitably drawn to the diversity of shapes in use, and the role played by senior engineers themselves in the proliferation of variety. The need for a coordinated response to a competitive challenge taking the form of standardization was by no means a novelty by this time. For example, Velkar has shown how the competitive challenge from German producers being experienced around 1880 in the wire industry eventually produced a response based upon voluntary, consensus based standardization and cooperation among the leading producers.³⁵

The standardization effort inaugurated in 1901 brought together five leading engineering institutions - initially and in addition to the ICE, the Institution of Mechanical Engineers, the Institution of Naval Architects, the Iron and Steel Institute, and later the Institution of Electrical Engineers.³⁶ Although large manufacturing concerns were represented, the major government procurement agencies provided a strong direction for early standardization work.³⁷

The ESC 'model' as it took shape was clearly articulated in a retrospective lecture some sixteen years later, in which Wolfe-Barry made clear that there was no attempt to create standards *ex cathedra* 'but only after the fullest discussion by all concerned'.³⁸ The principle of voluntarism among both producers and consumers was established to 'introduce order into a condition of things which had become more or less chaotic, or at any rate which urgently required intelligent regulation.'³⁹ Further, to ensure that work of economic value be undertaken, work would only be carried out after 'important representations.'⁴⁰ At no stage was it envisaged that the ESC should become a testing and certificating body, leaving the principle of *caveat emptor* as expressing 'the limitation of the

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³⁴ In fact the debate which provided the inspiration for the motion seems to have been rumbling for some years. The BSI's own account refers to a letter to the *London Times*, dated January 15th 1895 in which H. J. Skelton - a London based iron merchant - castigated both engineers and architects for specifying 'such unnecessary diverse types of sectional material for given work that anything like economical and continuous manufacture becomes impossible...' (quoted in Woodward, *Story of Standards*, p. 8).

³⁵ Velkar, 'British Wire Industry'. Velkar however stresses the role of government in the form of the Board of Trade as an arbitrator between producer and user interests.

³⁶ McWilliam, 'The first British Standards', p. 265.

³⁷ Unwin, 'Standardisation and its influence', p. 99.

³⁸ Wolfe-Barry, *James Forrest Lecture*, p. 337.

³⁹ *Ibid.*

⁴⁰ *Ibid.*

committee.’⁴¹ Here however, complementary services were provided by the newly established National Physical Laboratory (NPL), which had opened in 1902, for the creation of higher level scientific and metrological standards, as well as in providing testing and reference methods, some of which were carried out in-house.⁴² Finally, and ‘most important perhaps of all’ it was essential that the work of the Committee be ‘subject at all times to revision, so that improvement could be incorporated, and that the various trades should not become hide-bound, nor their methods stereotyped.’⁴³

The returns from the activities of the ESC can be gauged in a variety of ways. Its coverage can be seen in terms of the development of the committee structure. With the main committee now undertaking the administration of the ESC, Unwin reported that by 1908 the standardization work was undertaken by twelve sectional committees and 28 sub-committees. Three committees dealt with rolled steel sections - one for ships’ sections, one for bridges and other constructional material, and one for railway rolling stock and underframes. The other committees were responsible for locomotives, electrical plant, screw threads and limit-gauges, cement, cast-iron pipes and pipe flanges; additional committees were established for publications and finance.⁴⁴ A section for vitrified ware pipes was created in 1911, and two sections for the emerging automobile industry in 1912 - one for road material and one for motor vehicle parts.⁴⁵ The First World War had a clear impact on the demand for standardization work, with two new committees charged directly by the government with the coordination of the standards and specifications of the Air Board and Department of Aircraft for aircraft production and material for the war effort. Eventually, these two committees spawned 15 sub-committees on their creation in 1917.⁴⁶ By 1918 over 80 standards had been produced and the documents had become significant repositories of relevant codified technological knowledge.⁴⁷

Ultimately the realisation of the benefits from these British standards depends upon their up-take. As far as rolled steel was concerned, the creation of a standard list appears to

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⁴¹ *Ibid.*, p. 338.

⁴² Unwin, ‘Standardisation and its influence’, describes various instances in which the NPL was able to provide underpinning research as well as some certification activity.

⁴³ Wolfe-Barry *James Forrest Lecture*, p. 338.

⁴⁴ Unwin, ‘Standardisation and its influence’, pp. 99-100.

⁴⁵ McWilliam, ‘The first British Standards’, table 1, p. 267.

⁴⁶ British Standards Institution, *Fifty years*, p. 38.

⁴⁷ According to McWilliam, ‘The First British Standards’, the specification for Portland cement (BS 12) published in 1904, contained three test procedures for cement characteristics (p. 274).

have been remarkably successful. Wolfe-Barry's 1917 review provided some estimates of the use of a standard list for rolled steel parts - a joint product of the founding four sectional committees - shipbuilding, railway rolling stock, bridges and construction, and rails. Wolfe-Barry [had] 'asked leading manufacturers...[to provide] some estimate of the percentage in 1914 of their output which was produced in accordance with our standard specifications, and standard sections.'⁴⁸ These indicated that between 85-95 per cent of sections for both construction and shipbuilding were rolled to specifications from the standard list; 75 percent for tramway rails; 90 per cent for bull-head railway rails (primarily for domestic use as demanded by the railway companies); and 90 percent for flathead rails (primarily for export). Despite the success of the standard list for rolled steel, and indeed of the specification for cement, Wolfe-Barry reported very little standardization in locomotives built for domestic use (which he described as 'lamentable') but considerable progress in India where [he believed]:

'a broader view was taken, mainly I think, because Indian railways are under Government control, and was due to Lord George Hamilton, then secretary of state for India, who in 1901 instructed the locomotive superintendants of India to meet in conclave and arrive at a certain number of types suitable for that country.'⁴⁹

For rolling stock an analogous situation pertained, with some progress in India but reportedly nothing being done in Britain. Important as these early standards were, and the high benefit-cost ratios – which, with a high rate of diffusion were arguably achieved – they reflect a back-log of demand for standardization made possible by technological change in a few key sectors, and for steel products in particular. A situation had not yet been achieved in which the process of standardization broadly reflected 'steady-state' technological advance. In the next section, we consider how the increase in scope of the committee model established by the ESC and its evolution into a genuine 'national' standards setting agency, became integrated into a wider system of innovation.

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⁴⁸ Wolfe-Barry, *James-Forrest Lecture*, p. 344.

⁴⁹ *Ibid.*, p.343.

IV

While the period 1901-1918 and the experience of the First World War was important in establishing the viability of the ESC model of standardization, its continuing progress in the subsequent period may usefully be set within the wider industrial and political context. Here, ideas moved away from the received wisdoms of laissez-faire beliefs into a broader current sometimes described as the 'rationalization movement', and within which the ESC's development may be seen as one of a number of institutional 'experiments' in cooperation and coordination (as well as in government intervention) that influenced economic policy between the wars.⁵⁰ It seems a reasonable assertion that the work of the ESC represented one of the more successful of these initiatives, and where the complementarity of its activities with those of NPL - as noted above - seems to have borne fruit. During the war itself, the NPL was brought under the remit of the Department of Scientific and Industrial Research. The Department began to sponsor its own research deemed unsuitable for private effort, while also providing subsidies for the establishment of industry research associations. Early beneficiaries here include parts of the metal and engineering trades, textiles, leather industries, glass, laundries, grain milling, and food processing. Many of these research associations formed important links with NPL, which was itself now under the remit of the new ministry, thereby creating a wider research network which also began to include the universities.⁵¹

By 1918 the combined efforts of the ESC were deemed sufficiently important to warrant its incorporation as the British Engineering Standards Association (BESA), a change marking recognition that its activities had broadened considerably both at home and overseas.⁵² During the next decade, coverage had moved into new areas such as coal mining, paints and varnishes, petroleum, and illumination. In 1929 BESA received its Royal Charter which defined its objects and purposes, but these were broadly consistent with the strategy enunciated at its incorporation. However, the charter was amended in 1931 to reflect the widening of activities to include the standardization activities of the Association of British Chemical Manufacturers, while the name was changed a final time to the British

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⁵⁰ Discussed in, for example, Hannah, *Corporate Economy*, chapter 3, and Wilson, *British Business History*, chapter 5.

⁵¹ Sayers, 'The Springs', pp. 279-80.

⁵² At the same time the 'Kitemark' was launched as a trade mark (BSI, *Fifty Years*, p. 62).

Standards Institution (BSI). This action created a new tier of responsibility – with Divisional Councils - Chemical, Building, and (from 1932) Engineering - separating a General Council from the Industry Standards Committees and the numerous technical committees, which by 1929 already numbered around 500.⁵³ Indicators of the success of the ESC and BESA included a renewal of government attention, where the role of standardization in promoting productivity formed an important constituent of the factors ‘affecting the competitive position of British Industry’ addressed by the Balfour Committee on Industry and Trade, set up in 1924, and whose final Report appeared in 1929. Evidence was provided by BESA to the Committee during 1925 in which considerable attention was paid to the comparative development of formal standardization in Britain and elsewhere. This largely focussed on efforts in the US and Germany, and the role of competing national standards in export markets such as South America,⁵⁴ where concern was expressed about the use of standards in government procurement.⁵⁵ In evidence to the Committee, the Secretary of BESA referred to differences between standardization efforts between both Britain and the US, and with Germany, with which despite the broad similarities with the British institutions, the Secretary took the view that ‘...when one takes a German standard and comparing it with our own, one finds that our standard is not necessarily superior in quality, but it is in most cases more practical than the German standard.’⁵⁶ Whatever the merits of this argument, it certainly seems as if the German engineering community took to the process of standardization with alacrity. Germany was the first - in 1917 - of a number of European economies that had created national standards setting agency as variants of BESA – some 15 were created between 1917 and 1925. The Weimar Republic seems to have provided a fertile ground for both the rationalization movement in general and standardization in

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⁵³ Woodward, *Story of Standards*, p. 12.

⁵⁴ Board of Trade, ‘Balfour Committee Minutes’, p. 6878.

⁵⁵ From the beginning, export markets without colonial ties such as South America, were fundamental to the British standardisation efforts. However, the strong position of the British engineer in securing infrastructure projects associated with foreign outward portfolio investment, was threatened in many instances by insufficient standardisation and ‘the thorny subject of a general change of British standards’ to metric dimensions, which in his James Forrest lecture, Wolfe-Barry did not dare broach for fear he ‘might transform this staid meeting into one of raging controversy,’ (Wolfe-Barry, *James Forrest Lecture*, p. 347) and which the ESC should not take a view. The ESC had however recommended to Government that specifications should be ‘at once translated into French, Spanish, and Russian, with metrical equivalents for the British measurements and formulae’ (*ibid.*, p. 347), with local committees in the main (non-Empire) trading centres. Moreover it was important that the price of all publications should be reduced to a rate comparable with the US, ‘who sell their specifications for a quarter of a dollar or less’ (*ibid.*, p. 348). In fact funds from both Government and industry helped to achieve both aims.

⁵⁶ Board of Trade, ‘Balfour Committee Minutes,’ p. 6865.

particular.⁵⁷ German standardization efforts began in the war itself with the objective of standardizing ‘machine elements’, but by 1926 this had - like BESA - broadened in scope and was now operating under the name of the *Deutscher Normenausschuss*. Financially supported by the primary hub for rationalization - the *Reichs Kuratorium für Wirtschaftlichkeit* (Reich Board for Industrial Efficiency) - it acted as a ‘federation’ of various technical societies according to Karabasz, who also notes that, at the level of the individual enterprise, the distinct profession of standardization engineer was being developed, while some consulting engineers were beginning to specialise in standardization work. He also records a remarkable growth in the numbers of national standards produced in Germany - with over 2100 in existence by the end of the decade 1917-27.⁵⁸ Whether commensurate or not, this number was far in excess of 576 standards in the BESA catalogue by 1927;⁵⁹ here Karabacz suggests an emphasis on ‘dimensional’ standards - aimed at reducing variety. However the evidence does help to sustain the idea - consistent with the recent evidence presented in Shearer - that the rationalization movement in Germany was more than empty political rhetoric or a tool of the industrial capitalist, and that a standardization movement formed a substantial component of a drive for efficiency.⁶⁰ The data also suggest that assessments of the degree of success achieved through voluntary standardization in Britain should be qualified when compared to Germany. In fact the period established a long standing difference in the apparent size of the voluntary national standardization efforts between Britain and Germany which extended well beyond World War II and into the 1980s, prior to the harmonization drive prompted by the creation of a European Single Market.⁶¹

While the spread of a standardization model along lines similar to that in Britain both in Germany and in Europe provides some evidence of its viability, it needs to be noted that the US pattern of development remained a distinct one – and considerably more decentralised - although even here private-public partnership in standardization was boosted by the First World War. Coordination efforts during the war gave impetus to the creation of the American Engineering Standards Committee (AESC) in 1918 – which complemented the existing National Bureau of Standards - and whose founding members

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⁵⁷ See for instance Brady, *The Rationalization Movement*.

⁵⁸ Karabasz, *Simplification and Standardisation*, pp. 26-7.

⁵⁹ The figure comes from our own estimates (see section V below).

⁶⁰ Shearer, *Politics and the Rationalization Movement*.

⁶¹ See for example the comparative evidence in Swann *et al.*, ‘Standards and Trade Performance’.

included the 'Big 5' professional engineering associations, as well as the Departments of Commerce, Navy and War.⁶² In the period after 1918, rationalization in industry received considerable support from the Secretary for Commerce, Herbert Hoover, who established a Division for Simplified Practice as part of the National Bureau of Standards to achieve variety reduction, acting mainly as a catalyst to spur coordination through various trade associations. But there were clear differences in the development of standardization in the US when compared to either Britain or Germany. Neither the AESC nor its successors (ASA and ANSI) functioned quite like BESA, i.e. as a 'peak' standardization body, eschewing the introduction (as opposed to the endorsement) of standards. As described by Adams in 1919, standards development itself was the province of the many sponsoring bodies,⁶³ while in evidence to the Balfour Committee in 1925, BESA's secretary ventured that the AESC acted 'rather as a 'rubber-stamp' committee. The great difference between the Committee and ourselves is that we receive proposals and recommendations for standards, but we do not put a rubber stamp on them.'⁶⁴ The Committee was however more impressed by the work of the promotional work of the Division of Simplified Practice and by the relevance of American standards in export markets.

In summary, by the time of its name change in 1931, the BSI, founded and extended on the model of the ESC, had considerably broadened its coverage to embrace much of the manufacturing and construction industries, and now included chemicals. For the statistical analysis which is to follow, 1931 can be regarded as the date from which the BSI is linked to technological change on a broad front of the domestic economy, and one where there is evidence of developing institutional complementarities with other elements of Britain's innovation infrastructure. Moreover the institution had been imitated in a large number of European countries, including Germany, where the growth of the standards available to industry appears to have been considerably faster than in Britain in the decade after World War I. Standards development in the US took a different form, reflecting more pluralist and

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⁶² Adams, *Industrial Standardization*, p. 296. The founding associations were the American Society of Civil Engineers (ASCE), the American Society of Mechanical Engineers (ASME), American Institute of Electrical Engineers and the American Society for Testing Materials (ASTM), the American Institute of Mining (AIME) the American Institute of Electrical Engineers (AIEE). The AESC was the forerunner of the American Standards Association (ASA), which became the American National Standards Institute (ANSI).

⁶³ Adams, *Industrial Standardization*, p. 291-2.

⁶⁴ Board of Trade, 'Balfour Committee Minutes', p. 6946.

market oriented predispositions as well as the fact that the generally larger scale of much US enterprise had reduced the need for inter-company standardization.

V

Before moving on to an empirical model of the relationship between standards and productivity, we first consider our proposed measure of standards output. Following two of the studies described above,⁶⁵ we use the number of standards in the ‘catalogue’ made available by the BSI to producers, as providing a convenient starting point. At any one time, the catalogue comprises the cumulated publications of standards up to that time less retired or withdrawn standards, such that:

$$STAN_t = \sum_{i=-\infty}^t P_i - \sum_{i=-\infty}^t W_i \quad (1)$$

where $STAN_t$ is the measure of the standards catalogue at end of period t , P_i is the number of standards published, and W_i is the number of standards withdrawn (or retired) during any year i . $STAN_t$ is therefore a measure of the ‘stock’ of standards current at the end of t periods and which we argue serves as a proxy for the ‘flow’ of benefits to the economy during any interval of time t .

To justify our approach, it is helpful to think not so much of individual standards but in terms of the publications of a particular year, or put another way, a particular ‘vintage’. While the standards published within any vintage may be expected to create a positive net benefit to the economy, over time these benefits will decline, as the technology in which the standard is embedded becomes less relevant and the physical equipment to which it refers becomes obsolete. Consequently, the standards of a particular vintage are withdrawn from the catalogue. A few are declared obsolete, but the large majority are ‘replaced’ or ‘superseded’ by a newer standard, better fitted to the current technological and business situation. The declining efficiency of any vintage is thus reflected in its declining share of the overall catalogue. Our measure is therefore akin to measures of the fixed capital stock, but

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⁶⁵ Swann *et al.*, ‘Standards and Trade Performance’; Jungmittag *et al.*, ‘Innovation’.

instead of imposing a retirement pattern or rate of depreciation, we use actual withdrawals as a measure of the depreciation in the economic value of the standards stock.

Our data on the size of the catalogue were constructed by amalgamating two data sources. First what was known in the BSI as the 'History Book' – essentially a list of all British standard publications by year together with (partial) information regarding as to when they were withdrawn.⁶⁶ This source was discontinued as computerised records were introduced in 1985 and accordingly, from that date, we used the PERINORM database. However the History Book had listed over 18,000 publications by the end of 1984. Since PERINORM provided us with an accurate measure of the size of the catalogue (*STAM*) at any time after 1985, we used (1) to establish that about 36% of standards published by end 1984 had been withdrawn without being recorded. Estimates of withdrawals therefore had to be made for the period prior to 1985 in order to reconcile the two sources. Details of the precise method adopted can be found in the data appendix to this paper.

Figure 1 illustrates significant variations in growth rates of the catalogue by decade from BSI's creation in 1931, at which time we estimate that there were 717 current standards. Rapid growth rates can be observed in the decades 1950-1960 and once again between 1990 and 2000. By contrast, the two decades from 1970 to 1990 were periods of relatively sluggish growth. The variation in growth rates between 1931 and 2009 undoubtedly partly reflected deeper changes in the stance of economic policy. The context for standardization changed rather dramatically after the Second World War, when industrial productivity comparisons with the US came to the fore, and a new Labour administration, with a will for industrial intervention, saw standardization along US lines as a major vehicle for achieving enhanced productivity. Beyond the establishment of the Anglo-American Productivity Councils (AAPC), one of which was set up specifically to examine 'simplification'⁶⁷ (as the engineering community referred to variety reducing standards), the productivity drive put policy emphasis on cross firm standardization. By the late 1940s, the BSI was regarded by government as a major contributor to the process with increasing debate as to whether the more interventionist Labour government might move beyond the

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⁶⁶ We acknowledge the assistance of the BSI in providing us with a photocopy of the original History Book.

⁶⁷ AAPC, *Simplification in Industry*.

established principle of voluntarism - a position maintained by the Lemon Committee.⁶⁸ Moreover, after 1950, international agencies became an increasingly important source of new standards, notably via the International Organization for Standardization (ISO), which was established, with a secretariat in Geneva, in 1946,⁶⁹ and the International Electrical Commission (IEC), which resumed its work after the war. At the ISO, 50 technical committees had been established by 1949.

Figure 1
Average annual growth rates in the size of the BSI Catalogue 1931-2009
(Source: PERINORM, BSI History Book, and own estimates)

After 1960, Figure 1 clearly shows a progressive slow-down in the rate of growth of the catalogue by decade to a nadir in the 1980s. The slow-down in the decade 1960-1970 may simply indicate the loss of the interest shown in the early post-war period. Between 1970 and 1990 however, deindustrialization and other related factors almost certainly contributed to the deceleration. After 1990 however, the marked acceleration was largely determined by the enhanced role of standards in the creation of the European Single

⁶⁸ Established by the Ministry of Supply in 1948 and whose report was timed to coincide with the AACP report (Tomlinson and Tiratsoo, *Industrial efficiency*, p. 145). The emphasis on standardisation at this time was not only evident in the number of standards. Woodward, *The Story of Standards*, reports that the number of companies becoming members increased by 25% (p. 16).

⁶⁹ At the ISO, 50 technical committees were in existence by 1949. Woodward, *The Story of Standards*, p. 53.

Market. The biggest share of the new standards introduced into the catalogue in the last decade has its origin in the European standards setting organizations - CEN, CENELEC, and ETSI - although some of these have their ultimate origin in the international organizations such as ISO.⁷⁰ This new source of standards represented a considerable redeployment and ‘pooling’ of national resources at the European level. Although it is possible that some ‘dilution’ in the relevance of the catalogue has occurred as a result, the fact that many of these standards provide an efficient vehicle for technology transfer as well as the marketing of exports, especially within the EU, provides offsetting effects.

VI

Having considered a measure of institutional ‘output’ in the last section, we now turn to an assessment as to whether, serving as a proxy for technological activity based on standardization, our measure is associated with long-run productivity growth. For this purpose, we report estimates of a production function for the whole UK economy, which is augmented by the standards measure. The period chosen for the analysis is 1931-2009, a period over which the BSI, as discussed in section IV, having incorporated the chemical manufacturers, can be regarded as a national institution with extensive linkages across the economy and whose output reflects technological change on a broad front.

A standard production function with both conventional inputs and technological progress can be written as:

$$Y_t = A_t f(K_t, L_t) \quad (2)$$

where Y_t , K_t , L_t represent period t output, capital input, and labour input respectively while A_t is a multiplicative factor representing the level of technology. If the latter is partly determined exogenously and partly by the current stock of standards, we have:

$$Y_t = e^{\lambda t} STAN_t^\gamma f(K_t, L_t) \quad (3)$$

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⁷⁰ DTI, *Empirical Economics of Standards*, chapter 2.

where λ is an exogenous time trend representing unobservable influences on output, γ is a parameter measuring the elasticity of output with respect to the standards stock, and $STAN_t$ is the standards stock at time t . Using a Cobb-Douglas representation and assuming constant returns to scale allows us to express (3) in terms of labour productivity:

$$\frac{Y_t}{L_t} = e^{\lambda t} STAN_t^\gamma \left(\frac{K_t}{L_t}\right)^\alpha \quad (4)$$

where α is the elasticity of labour productivity Y_t/L_t with respect to the capital-labour ratio, K_t/L_t . Taking logarithms of the relationship in (4), and setting $y_t = \ln(Y_t/L_t)$, $k_t = \ln(K_t/L_t)$ and $stan_t = \ln STAN_t$, it is possible to obtain an estimating equation by adding a normally distributed error term u_t :

$$y_t = c + \lambda t + \gamma stan_t + \alpha k_t + u_t \quad (5)$$

where c is a constant. In (5), the estimation of γ is of special interest.

Our data sources for output (gross value added), labour input (total hours of work), and capital (proxied by the gross capital stock), are mainly based on UK Office for National Statistics (ONS) data, and for earlier periods on Feinstein's contribution.⁷¹ These are described in more detail in the data appendix. Figure 2 plots the behaviour of the variables in expression (5) and is drawn using a log-scale with 1931=100. The figure illustrates the considerably faster growth in the standards stock than for either labour productivity or the capital-labour ratio. Significantly, all of these variables were found to be integrated of order one, which has implications for our estimation strategy.⁷² Figure 3 displays the same variables expressed as annual percentage rates of growth.

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⁷¹ C. H. Feinstein, *National Income*.

⁷² Unit root test results are provided in Appendix II.

Figure 2:

Levels of Gross Value Added per hour of work (Y/L), Gross Capital Stock per hour of work (K/L) and the end year stock of BSI standards ($STAN$)

(Sources: ONS; Feinstein, *National Income*; Dimsdale *et al.* 'The UK recession')

Figure 3

Year-on-Year % changes in Gross Value Added per hour of work (Y/L), Gross Capital Stock per hour of work (K/L) and the end year stock of BSI standards ($STAN$)

(Sources: as for figure 2)

As the pit-falls of *directly* estimating an equation such as (5) – where the variables are characterised by unit roots – are well-known, our main requirement resides in establishing a cointegrating relationship between labour productivity, the capital-employment ratio and standards. The current literature allows for the possibility of there being more than one cointegrating vector, and given our small sample size (in observations rather than time) we use the S2S estimator developed by Brüggemann and Lütkepohl,⁷³ who report better small-sample properties than the maximum likelihood procedure of Johansen.⁷⁴ Significantly, the presence of cointegration implies the existence of a valid vector error correction (VEC) representation of the data.⁷⁵ Econometric experiments led to the selection of a VAR(3) model in y , k and $stan$, as well as a time trend, t , and an extended impulse dummy ($WARDUM$).⁷⁶ Accordingly, a single cointegrating equation was estimated,⁷⁷ with the signs of coefficients in line with our priors:

$$y = -0.91 + 0.646 k + 0.100 stan + 0.009 t \quad (6)$$

(0.042) *   (0.055) **   (0.003) *

The estimated elasticity of 0.10 on $stan$ suggests that standards have been associated with a considerable amount of long-run productivity growth (nearly 0.5% per annum between 1931-2009), although this is less than the contribution of the unobserved factors (0.9% per annum) or that from the growth in the capital-employment ratio (1.2% per annum).

The coefficient on the capital term at 0.646 is rather higher than capital's share in value added, suggesting the presence of a wedge between private and social rates of return. While this can arise in a number of ways – through the provision of valuable information to

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⁷³ Brüggemann and Lütkepohl, 'Practical Problems', estimate a cointegrating equation using a small dataset (96 observations) with three endogenous variables and hence similar to ours (79). The small sample size also suggests using a parsimonious model specification. Our model was estimated using JMulTi 4.2 (<http://www.jmulti.de/>).

⁷⁴ Johansen, 'Statistical Analysis'.

⁷⁵ Johansen and Juselius, 'Maximum Likelihood Estimation'.

⁷⁶ Three impulse dummies were also included to address residual outlier problems (see for example: Doornik, 'Inference' or Klemp, 'Prices'). This had the effect of ensuring that the residuals were normally distributed, homoscedastic, and independent across time. A complete discussion of our testing procedure is provided in the Appendix.

⁷⁷ Standard errors are given in parentheses. Significance levels (one-tailed test) are denoted as: *=1%, and **5%. To check robustness, we re-ran the estimation omitting the years characterised by the global financial crisis (2008-2009). Our results were similar: we found a single cointegrating vector of the form:

$$y = -0.869 + 0.629 k + 0.095 stan + 0.01 t$$

(0.042)*   (0.055)**   (0.003)*

competitors for example - the transmission of technological knowledge accompanying fixed investment is clearly potentially relevant in the present context, providing impetus for standardization. On the other hand, causation is likely to go the other way – with standards providing the confidence to make forward looking investments. These possibilities suggest that the dynamics behind the cointegrating relationship may be of interest.

The estimated short-run dynamic counterpart to our long-run relationship is presented in table 1. Our results show that behind (6) is a system of feedback mechanisms, which allow us to make inferences about the response of variables to economic shocks, and possible directions of causality running between the variables themselves. The results reveal that standards display ‘weak exogeneity’ and are not ‘Granger caused’ by the other model variables.⁷⁸

In the case of weak exogeneity, we note that the coefficients corresponding to the cointegrating equation error (e_{t-1}) term in table 1 relate to the speed with which each variable (Δy , Δk , $\Delta stan$) adjusts to restore equilibrium following a shock to the system. Significantly, e_{t-1} is not statistically different to zero in the standards equation. This is consistent with intuition, in that standards setting is a process characterised by an institutional momentum, with the publication of a standard occurring only at the end of a possibly lengthy period of committee deliberation and largely independent of current economic circumstances.⁷⁹ However, weak exogeneity does not preclude standards from responding to, or indeed influencing, changes in labour productivity and the capital-employment ratio with a one period lag or more.

The degree of inertia which characterises standard setting suggests that Granger (non-) causality tests may also be of interest. Here, we rejected the null hypothesis that the stock of standards does not Granger-cause labour productivity and the capital-employment relationship.^{80,81} By contrast, conventional inference suggested we accept the null hypothesis

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⁷⁸ Together these conditions imply ‘strong exogeneity.’

⁷⁹ The error terms associated with labour productivity (Δy_t) and the capital-labour ratio (Δk_t) equations are highly significant, meaning neither of these variables are weakly exogenous; all of the adjustment back to the long-run equilibrium in (6) is done by these variables. That they are oppositely signed means they adjust in opposite directions to restore equilibrium.

⁸⁰ We used the Block Granger (non-) causality testing framework described in Lütkepohl, *Introduction*, Sec. 3.6.3., and made available in JMulti 4.2, which explicitly allows for the fact that, in a system of equations, complex interdependencies may exist, e.g., two or more variables can Granger-cause a single variable, and vice versa. Further analysis using impulse responses (not presented) pointed to the presence of capital adjustment costs (for recent UK evidence see Groth, ‘Quantifying UK Capital’).

⁸¹ The p-value associated with this test (i.e., the probability of falsely rejecting the null hypothesis) was 0.0246.

that labour productivity and the capital-employment ratio do not Granger-cause standards.⁸² This conception of causality therefore appears to run in one direction only, namely from standards to the other variables, sustaining the idea that standardization promotes economic growth rather than vice-versa.

In summary, both the cointegration analysis of the long-run relationship and our estimates of short-run dynamics around the long-run, provide corroboration for our earlier analysis which suggests that voluntary consensus based standardization, coordinated at a national level, has historically been a significant driver of technological change and long-run productivity.

VII

This paper has explored the development of voluntary consensus based standards – coordinated at a national level at the BSI and its forerunners – and considered its relationship to economic growth in Britain. The historical record, coupled with an econometric analysis that utilises the size of the standards catalogue of the BSI as a proxy for the extent of learning and knowledge generated through standards, indicates that this path of learning has exerted a positive impact on British economic growth.

In terms of the history of the creation of the BSI, we emphasised the role of an elite cadre of British engineers, whose position was threatened both at home and in export markets by the increasing international challenges at the beginning of the 20th century. The emergent model of committee based standardization proved remarkably robust: it was not only imitated by other European economies, but has persisted, in largely unmodified form. Moreover it provided a novel and distinct mode of collective learning which, at least partly, substituted a mechanism for achieving external economies of scale across firms, for one based on vertical integration and economies internal to the firm - an alternative path of learning recognised as being of greater importance in the US. In contrast, Germany adopted a similar model of standardization, but one with possibly even stronger linkages to the processes of technological change than in Britain.

Given an increasingly recognised role of standardization for affecting technological change and economic growth, the paper used cointegration analysis to demonstrate the association between standards and long-run labour productivity growth for the period 1931-

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⁸² The p-value = 0.6714.

2009, a period over which the BSI and associated institutions (in for example, certification and testing) was firmly embedded into the broader processes of innovation. Our results suggest that the strong growth of the standards made available via the BSI catalogue, has been associated with a large proportion of measured technological change. We do however urge caution regarding the interpretation of this latter finding; rather than argue for a separate and independent role for institutional standards in promoting economic growth, we suggest that it represents an important component of a particular path of learning, in which the process of standardization itself cannot easily be separated from other factors, most importantly imitation and organizational change, and the diffusion of more radical innovation. There was also an indication that standards may be important for capital accumulation, certainly a topic for further investigation. Viewed in this the way, the development and maintenance of the standards catalogue may be interpreted as a coupling device, linking the deep drivers of productivity growth, such as human capital formation and innovation, with the orderly development of markets.

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Appendices

Appendix I: Data sources

Output (Y) – For 1948-2009, the series is based on estimates of gross value added at constant basic prices (series ABMM) from the ONS 2013 Blue Book database (<http://www.ons.gov.uk/ons/rel/naa1-rd/united-kingdom-national-accounts/index.html>). Earlier years use GDP at constant factor cost from Feinstein, C.H., (*National Income and Expenditure and Output, 1855- 1965*, Cambridge (1972)) table 5, series 12.

Capital Input (K) – For 1948-2009, the series uses ONS estimates of gross capital stock (excluding dwellings) at constant replacement cost published in 2011, but now discontinued. For earlier years, the estimates of gross capital stock are from Feinstein, C.H., (*National Income and Expenditure and Output, 1855-1965*, Cambridge (1972)), table 43.

Labour Input (L) – Estimates of whole economy hours of work. For 1971-2009: ONS estimates of all UK persons aged 16+ in employment (4 quarter averages), series MGRZ. This is adjusted for hours of work by series YBUS. Both series downloaded from: <http://www.ons.gov.uk/ons/rel/lms/labour-market-statistics/august-2014/dataset--labour-market-statistics.html> (accessed 18th January 2015). For 1959-1970: series for UK Workforce in Employment (June), *Employment Gazette Historical Series No 3*, 1992. For 1928-1959: Feinstein, C.H., (*National Income and Expenditure and Output, 1855-1965*, Cambridge (1972)), table 57 series 3. Adjustments for hours of work up to 1970 uses hours data from Dimsdale *et al.*, 'The UK Recession,' constructed from Mitchell, B.R., *British*, table 19 (col. 2), p.147, average hours per week (after allowing for part-time workers).

Stock of Standards ($STAN$): Estimates of the total stock (catalogue) of standards for 1985-2009 are taken from PERINORM - a database produced by BSI, the Association Francaise de Normalisation (AFNOR), and Deutsches Institut für Normung (DIN) - and BSI Online. These allow for exact calculation of equation (1) in the text. For 1901-1984 estimates of the size of the catalogue are based upon a printed record of all standards published by year made available to us by the BSI (the 'History Book'). This also contained information on 64% of all withdrawals of standards in the same period. For some standards published in the period 1901-1984 there is no evidence of withdrawal but which were clearly unavailable in 1985. These standards were allocated withdrawal dates according to our calculations (from standards whose disappearance was recorded) of 'hazard rates' (the probability that a standard will be withdrawn in period t given that it has survived to period $t-1$). Pooling the evidence across publications by decade suggests that the hazard rate increases steadily up to about 10 years and then is relatively constant at 9-10%. The pattern is rather similar for the vintages of different decades, and so we imposed a constant pattern for all standards for which we had no firm retirement dates from the History Book. Experiments with altering these hazard rates had little important impact on our estimates of the size of the BSI Catalogue in any particular year. The actual hazard rates used to achieve balance between the History Book and the size of the catalogue in 1985 as recorded in PERINORM were: 0-2 years: 0.008; 2-5 years: 0.027; 5-10 years: 0.059; 10-20 years: 0.093; 20-30 years: 0.102; 30+ years: 0.100. Only minor adjustments were then required.

Appendix II: Unit root tests

We used unit root tests developed by Ng and Perron, ‘Lag length selection’, which have superior finite sample properties when compared to the better-known ADF and Phillips-Perron tests. Appendix table 1 reports our findings, in which the null hypothesis of a unit root for each series cannot be rejected. For the series in levels, results are shown in Part A of the table, where the inclusion of a time-trend reflects the trending nature of our data. This is confirmed by visual inspection of figure 2 in the main text. Each series was also first-differenced and tested for a unit root, albeit with the omission of a time-trend due to the observed mean-reversion of the each series (see figure 3 in the main text). Part B of the table shows that in every case the null of a unit root for the first-differenced series was unanimously rejected, indicating that labour productivity, the capital-employment ratio and the stock of standards are $I(1)$.

Appendix table 1. Results of Ng and Perron unit root tests^{a,b}

Part A: Intercept and trend						
Levels	MZ_{α}	MZ_t	MSB	MPT	Lags ^c	Reject H_0 ?
y_t	-3.340	-1.266	0.379	26.759	0	No [†]
k_t	-2.745	-1.088	0.396	30.603	1	No [†]
$stan_t$	-3.400	-1.273	0.375	26.225	1	No [†]
Critical values						
1%	-23.8	-3.42	0.143	4.03		
5%	-17.3	-2.91	0.168	5.48		
10%	-14.2	-2.62	0.185	6.67		
Part B: Intercept only						
First differences						
Δy_t	-20.618	-3.107	0.151	1.155	2	Yes ^{††}
Δk_t	-11.097	-2.301	0.207	2.422	4	Yes ^{†††}
$\Delta stan_t$	-8.907	-2.098	0.236	2.799	2	Yes ^{†††}
Critical values						
1%	-13.8	-2.58	0.174	1.78		
5%	-8.1	-1.98	0.233	3.17		
10%	-5.7	-1.62	0.275	4.45		

^a Null hypothesis: *unit root is present*.

^b MZ_{α} and MZ_t are modified versions of Phillips (1987) and Phillips and Perron (1988); MSB modifies Bhargava's (1986) test; MPT is a modified version of the Elliot *et al* (1996) point-optimal test. For complete descriptions of these tests, and the references listed above, see Ng and Perron, ‘Lag length selection’.

^c Lag length automatically selected using the modified Akaike Information Criteria (MIAC) as recommended in Ng and Perron, up to a maximum of four lags.

[†] Only possible to reject the null of a unit root at significance levels considerably greater than 10%; ^{††} All tests reject the null of unit root at the 1% level; ^{†††} All tests reject the null of a unit root at the 5% level.

Appendix III: Lag length determination, residuals tests, and cointegration

To find the appropriate lag-length for a three equation vector auto regression (VAR) we estimated an unrestricted VAR given by:

$$Z_t = \phi_0 + \sum_{i=1}^p \phi_i Z_{t-i} + \Xi D + \psi_t, \quad \psi_t \sim iid N(0, \Psi) \quad (A1)$$

where p denotes the number of lags, ϕ_0 is a 3×1 vector of constant terms, ϕ_i is a 3×3 matrix of coefficients, and Z_t denotes a 3×1 vector of variables such that:

$$Z_t = \begin{bmatrix} y_t \\ k_t \\ stan_t \end{bmatrix} \quad (A2)$$

D represents a deterministic $j \times 1$ vector containing j regressors such as a linear time trend and dummy variables, and Ξ is a $3 \times j$ matrix of associated coefficients. Finally, ψ_t is a 3×1 vector of *i.i.d.* errors while Ψ is a 3×3 covariance matrix. The equations in the system therefore contain a common set of lagged and deterministic regressors. With respect to the elements of D , we included a time trend, t , and the extended impulse dummy (*WARDUM*) capturing the World War II years.

The Schwarz-Bayesian information criterion suggested a lag-length of two (Appendix table 2, Part A), which is plausible given the small sample-size and annual nature of the data; however, the associated model residuals were characterised by heteroskedasticity, non-normality, and a high degree of autocorrelation. To address this issue the lag-length was increased to three as suggested by Juselius, *The Cointegrated VAR Model*. It was also necessary to include a small number of impulse dummies (for 1991, 2008 and 2009) to deal with residual heteroskedasticity and non-normality. These procedures ensured that the residuals were neither serially-correlated (Lagrange Multiplier based tests, Appendix table 3, Part A), nor subject to heteroskedasticity (ARCH-LM tests, Appendix table 3, Part B), and multivariate normal (Jarque-Bera statistic, Appendix table 3, Part C). Further, the inverse roots of the characteristic polynomial were found to lie within the unit circle, indicating that the VAR satisfied the stability condition.

When testing for cointegration, the inclusion of dummy variables in our VAR(3) specification necessitated a statistical framework which provided correct critical values; we therefore used the tests proposed by Saikkonen and Lütkepohl, 'Intercept; 'Trend'; 'Structural'). Cointegration test results are presented in Appendix table 2, Part B, and indicate the existence of a single cointegrating vector at the five percent level, which implies that the model can be estimated as a vector error correction model. Expression A1 is hence manipulated to read:

$$\Delta Z_t = \pi + \Pi Z_{t-1} + \sum_{i=1}^{p-1} \gamma_i \Delta Z_{t-i} + \Xi D + \varepsilon_t \quad (A3)$$

where π is a vector of constant terms, and $\Pi = \alpha\beta'$, such that α is a matrix containing 'speed of adjustment' parameters and β is a matrix containing the (long-run) coefficients of the cointegrating vector. Since our model is characterised by a single cointegrating vector,

drawing valid statistical inference from the model parameters is possible as identification is not an issue.

Appendix table 2. Lag length criteria and the results of Saikkonen and Lütkepohl's cointegration tests

Part A: Lag order selection criteria	
Lag length	SBIC
0	-7.262
1	-14.646
2	-15.118
3	-14.922
4	-14.718
5	-14.356
6	-13.973

Note: numbers in **bold** letters denote the selected lag length. Maximum lag order set to six lags.

SBIC denotes the Schwarz-Bayesian information criterion (calculated as in Lütkepohl, *Introduction*, p.132).

Part B: Cointegration test results

<i>Hypothesised number of cointegrating vectors</i>	Likelihood ratio statistic	Critical values			
		10%	5%	1%	<i>p</i>-value
None*	31.18	26.07	28.52	33.50	0.022
At most one	7.63	13.88	15.76	19.71	0.590
At most two	0.20	5.47	6.79	9.73	0.980

Notes: Denotes rejection of null hypothesis of cointegration, based on a VAR(3);

Critical values obtained using response surfaces according to Trenkler, 'Determining p-values'.

Appendix table 3: Residual tests for autocorrelation, heteroskedasticity and non-normality

Part A: Lagrange multiplier (LM) test results for residual autocorrelation^a

Lags	LM statistic	p-value	LMF statistic ^b	p-value	df
1	12.9614	0.1644	1.1828	0.3104	9
2	21.2666	0.2662	0.9431	0.5283	18
3	32.4407	0.2162	0.9490	0.5424	27
4	45.2405	0.1390	1.0061	0.4695	36
5	69.4156	0.0112	1.3281	0.1082	45
6	82.6192	0.0073	1.3543	0.0838	54

^a H₀: residuals are serially uncorrelated; **df** denotes degrees of freedom.

^b LMF statistic based on Edgerton and Shukur, 'Testing'.

Part B: Multivariate ARCH-LM tests^c

Lags	LM statistic	p-value	Df
1	40.8280	0.2666	36
2	73.7240	0.4215	72
3	102.7699	0.6241	108
4	132.9177	0.7360	144
5	176.1228	0.5677	180
6	208.7116	0.6265	216

^c H₀: residuals are multivariate homoskedastic.

Part C: Residual tests for non-normality^a

Residual component	Skewness	χ^2	p-value	df
U_y	0.205	0.594	0.441	1
U_k	0.081	0.094	0.759	1
U_{stan}	-0.354	1.781	0.182	1
Joint		2.469	0.754	3
Residual component	Kurtosis	χ^2	p-value	df
U_y	3.926	3.980	0.046	1
U_k	2.774	0.091	0.763	1
U_{stan}	3.343	0.696	0.404	1
Joint		4.767	0.190	3
Residual component	Jarque-Bera		p-value	df
U_y	4.575		0.102	2
U_k	0.185		0.912	2
U_{stan}	2.477		0.290	2
Joint	17.495		0.863	6

^a H₀: residuals are multivariate normal.

Notes: Residual covariance (Urzuá) orthogonalisation used. Similar results were obtained using the alternative procedures of Doornik and Hansen, 'An omnibus test', and Lütkepohl, 'Introduction'.

df denotes degrees of freedom.