'HARDWARE IS HARD': MANUFACTURING STARTUPS IN AN URBAN TECHNOLOGY CLUSTER

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Abstract [148 words]

Studies of urban technology clusters have rarely looked at startups involved in manufacturing, aka 'hardware'. It is an open question whether archetypal start-up entry and growth pathways apply to these activities, and whether entrants benefit from locating in urban technology cores. I combine semi-structured interviews and microdata to explore the hardware cluster in Stockholm, one of Europe's leading tech hubs. I find a growing milieu with much economic potential. However, technology / product complexity, a lack of informed angel/VC investors and a limited acquisitions culture typically put entrants on much slower, revenue-driven pathways than software-focused counterparts. Similarly, participants report only limited affordances of cluster location. Many exploit linkages to Sweden's rich electrical engineering ecosystem via supply chains, hiring, partnerships and knowledge spillovers - but co-ordination failures suggest overall connections are sub-optimal. These findings imply a new set of potentially valuable policy interventions in the industrial policy tradition.

Keywords: Industry 4.0, ICTs, innovation, manufacturing, clusters, local economic development

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1/ Introduction

Like many industries before it, manufacturing is being ‘disrupted’ by new technology. This ‘Fourth Industrial Revolution’ (Schwab, 2017) or ‘Industry 4.0’ (Brettel et al., 2014) promises substantive productivity and growth effects via the application of technologies such as sensors, nanotech, RFID chips, robotics, machine learning and AI to a vast range of industrial settings (Brynjolfsson and McAfee, 2014). The general purpose nature of many of these technologies (Bresnahan, 2010) are said to promote recombinant growth (Kremer, 1993) both through the reconfiguration of existing production lines, products and services, and the development of entirely new ones.

Much existing analysis on the Fourth Industrial Revolution / Industry 4.0 has focused on *users* and more broadly, on industry awareness and levels of readiness in existing businesses (Brettel et al., 2014; Lee et al., 2014; Lee et al., 2015; Schwab, 2017). In contrast, this paper looks at specialised Industry 4.0 *producers*, specifically tech companies that combine software and programming expertise with a physical product or service derived from a physical product: ‘hardware’ firms in tech industry parlance. Given that the innovation and growth gains of Industry 4.0 are driven by the underlying ICTs, technology firms that should be central to these shifts. However, such businesses are under-explored in the existing literature.

The paper also explores whether some key stylised facts about tech startups in general hold for hardware startups. Two truisms about ICT are first, that entrepreneurship and startups drive innovation in the industry, with the most successful entrants either scaling through injections of VC funding, or being acquired by major players (Lerner, 2009; Kerr et al., 2014) and second, that young tech firms thrive in dense clusters, either in urban (London, New York, Berlin) or suburban / campus (Silicon Valley, Route 128) settings where they exploit a range of matching and learning economies (Saxenian, 1994; Duranton and Puga, 2004; Hutton, 2008; Chatterji et al., 2014).

Some open questions are: whether such classical startup pathways are suitable for hardware-based innovations; whether manufacturing-focused startups evolve through these pathways, or whether they develop alternative development trajectories; and whether/how hardware startups gain from the dense co-location that benefits software and content-focused entrants. I explore these questions using a mixed methods case study of hardware startups in Sweden, focusing on the Stockholm area. Sweden – and Stockholm – makes a strong test case.

First, hardware startups are located in a thriving cluster. Stockholm is one of Europe's leading technology hubs, with both thousands of young tech companies and some global players such as Skype, Spotify, Mojang and Klarna (Semuels, 2017). Overall, Swedish ICT industries are highly clustered, with Stockholm county dominating (in 2012, over 50% of all workers in tech industries were based in the area (Giertz, 2015a), and a substantial technology campus just outside the city in Kista's 'Science City'.

Second, entrants are positioned in a rich ICT milieu. Sweden's industrial heritage – in particular, its historic strengths in electrical engineering and mobile communications – mean that hardware firms can potentially draw on a rich 'ecosystem' of high-value manufacturing knowledge, suppliers / collaborators, and a thick labour market of skilled / experienced workers (Brown and Mason, 2014; Spigel, 2017). Unlike Germany, which combines large conglomerates with the 'Mittelstand' of small and medium-size firms, Sweden's industrial economy remains dominated by large MNEs, plus a cadre of specialist ICT consulting companies (Gens et al., 2015; Giertz, 2015a). Furthermore, in the early 2000s Ericsson shed around 50% of its workforce: many laid-off workers have either started their own businesses, or moved into consultancy roles, diffusing technical know-how further through the economy (Chaminade et al., 2010).

Third, national and local policymakers are actively trying to encourage new firm formation and development, to support ideas generation, and to link ecosystem actors. Sweden has a tradition of hands-on industrial policy, which includes both measures to develop 'Industry 4.0', by encouraging the development and diffusion of manufacturing ICTs, and a range of policies to promote entrepreneurship and new firm formation [REFs]. Much of this has been in response to the so-called 'Swedish Paradox' – high levels of R&D spending but low productivity (Bitard et al., 2008; Kander and Ejermo, 2009), which, it is argued, may be partly explained in

Schumpetarian terms by a lack of new entrants who bring new ideas to the market (Aghion et al., 2009).

This setting also raises some specific local questions. To what extent can public policy goals for Industry 4.0-driven growth be achieved through promoting technology entrepreneurship? Can a US-style startup culture be successfully imported into the Swedish business context? How far do hardware startups benefit from location in the larger Stockholm technology milieu?

The rest of the paper is organised as follows. Section 2 sets out the methodology. Section 3 provides a general framework, and Section 4 provides more detail on the Swedish case. Section 5 summarises the statistical analysis, while Section 6 gives findings from the qualitative analysis. Section 7 concludes.

2/ Data and design

This case study combines secondary sources (both academic and government studies of the Swedish ICT sector and the Stockholm cluster), analysis of firm and worker microdata, plus interviews with two groups of firms and with policymakers and other ecosystem actors. This cross-perspective, multi-level approach is suitable for an exploratory analysis such as this one (Gordon, 2006), and is similar to studies of other urban tech clusters (Power and Jansson, 2004; Hutton, 2008; Pratt, 2009; Nathan and Vandore, 2014).

2.1 / Quantitative analysis

The quantitative analysis uses microdata from the Statistics Sweden MONA database for the years 2007-2012 inclusive. I build industry and municipality-level panels from firm and worker-level microdata. The industry-level panel consists of 3,583 4-digit industry*year observations for 2007-2012. The municipality-level panel consists of 1,752 area*year observations for the same time period. Further details of the build are available on request.

To identify the set of tech firms that are Industry 4.0 producers, I start with a set of 'science and tech' industries drawn from an international benchmarking exercise conducted by the UK Office of National Statistics (Harris, 2015) and defined using 5-digit SICs. Drawing on the literature, I refine this to proxy 'Industry 4.0' producer sectors, dropping a number of content activities (publishing, media, music, advertising) and science /health activities (life sciences, health) except where SIC descriptors directly pertain to R&D and/or manufacturing. I then crosswalk this to 4-digit SICs, which is identical to the NACE Rev 2 /SNI07 codes used in Sweden and other EU states. I also select a set of STEM occupations from NESTA (Bakhshi et al., 2015), crosswalking these from UK SOC2010 occupation codes to SOC2008, then to the international ISCO08 and ISCO88 standards. The latter is identical to the SSYK-96 codes used in the Swedish data. Final lists of industries and occupations are given in the appendix, in Tables A1 and A2 respectively.

2.2 / Qualitative analysis

The qualitative analysis with firms draws on two sampling frames. The first is a hardware-focused co-working space in central Stockholm: members are typically under five years old and with less than 10 staff [hence COWORKING]. All tenants were contacted, yielding 11 interviews, a response rate of 39%. The second sampling frame is a business membership network of around 80 hardware firms, set up within the past decade and now with about 80 members, typically more established companies with workforces of 10-100. In this case, the sample was restricted to firms based in Stockholm municipality or with significant presence in the area [hence CITY]. Companies were contacted in waves, yielding five interviews, a response rate of 17%. Other stakeholder interviews were developed via snowballing and include policymakers (staff in national agencies and local government) and industry intermediaries (university commercialisation offices, industry networks/platforms and co-working space managers). All interviews were recorded and transcribed. Interviews with firms were open coded by hand [REF], then validated using topics generated through feature extraction and topic modelling (Benoit, 2018; Roberts et al., 2016).[1] Policy/stakeholder interviews were open coded by hand. In what follows firm interviews are prefixed F, policymakers P, industry intermediaries I.

3 / Framework

3.1 / Defining Industry 4.0

‘Industry 4.0’, the ‘Industrial Internet’ and the ‘Fourth Industrial Revolution’ are fuzzy terms with no standardised definitions (Giertz, 2015a; Gens et al., 2015). Its components can usefully be seen as a ‘technology-product-industry space’: that is, an evolving set of technologies, product/service applications and industry settings.

Commonly cited Industry 4.0 technologies include sensors and radio chips, AI; machine learning; 3D printing, nanotech and cloud computers. All of these involve ‘the internet connected to the real world’ [I26]. Many of these have general purpose characteristics (Bresnahan, 2010; Perez, 2010) and can be applied to a vast range of settings (Brynjolfsson and McAfee, 2014). Applications cover existing activities (such as automated production lines), computerised/digitised products (such as medical devices) and components (such as airbags). They also include wholly new or ‘recombinant’ use cases (Kremer, 1993), such as new ‘smart objects’ of varying complexity (such as wearables or drones). These new products typically require associated software, in apps and or other control systems. Cutting across this, we can think of a range of services based on the above, especially leasing, data and analytics (servitisation), consultancy and training [P20].

Almost all manufacturers could be *users* of these new technologies. This paper focuses on the (much smaller) set of *producers* – firms whose sole or principle output is a product/products in the Industry 4.0 technology space, or a service/services derived from such product. From a tech industry perspective, this technology / industry space is usually thought of as ‘hardware’ [I22, I26, I23]. Even so, it is still

[1] Text analysis and topic modelling using quanteda (Benoit, 2014) and stm (Roberts et al, 2016) in R. Coding and analysis in Dedoose.

very diverse: firms interviewed for this project variously identified as not only as hardware but also ‘tech’, ‘internet of things’, ‘medical technology’, ‘consumer electronics’, ‘automation systems’ or ‘industrial internet’ (see Section 5).

Following Freeman (1991) and Perez (2010), we can place these components in a larger, dynamic ‘technology system’, that is, a set of multiple technologies and its linked network of producers, suppliers, distributors and users. Technology systems benefit from (potentially substantial) internal spillovers. Perez argues that as 'technologies interconnect and tend to appear in the neighbourhood of other innovations' [*p187*], innovations in one part of the space tend to induce complementary (e.g. downstream) innovations in other parts. This fits the characteristics of the Industry 4.0 space outlined above.

The social and economic significance of such a system depends on whether it is essentially a series of incremental innovations within an existing technology regime (Geels, 2002; Geels and Schot, 2007), or part of a transition to a new regime or paradigm (Nelson and Winter, 1982; Dosi, 1982; Perez, 2010). There is a vigorous debate about the transformative potential of ICT as a whole, casting optimists (e.g. Mokyr (2013; 2015; Brynjolfsson and McAfee, 2014) against pessimists (Gordon (2016), Cowen (2011)). This paper provides some insight into these larger questions by looking at change at firm and industry level, both in terms of new inputs to production, perceived spaces for innovation, and broader changes in organisation behaviour (Perez, 2010). The focus on producers is a focus on the ‘motive’ and ‘carrier’ branches of the paradigm, in Perez’ language.

3.2/ Tech firm workflows

Hardware firms are knowledge-intensive businesses in which symbolic and physical product / service creation is a central activity. How this and other workflows are organised is a key question for this paper. As Mudambi (2008) points out, value creation is mostly created at the upstream and downstream ends of a production function: ICTs, in theory, allow ever finer levels of disaggregation and control. Nevertheless, while the costs of organising across long distances have fallen, the value of physical proximity for complex activity remains high, especially for building relationships, exchanging codified information and observing others (McCann, 2008; Sturgeon et al., 2008; Glaeser, 2011). A number of studies have highlighted tools such as project-based organising (Grabher, 2002), virtual communities (Grabher and Ibert, 2014)) and online tools (Bathelt et al., 2004; Bathelt, 2005) to mimic face to face. In general, small tech companies both make extensive use of these tools *and* tightly cluster into urban space (Chapain et al., 2010; Nathan and Vandore, 2014; Martins, 2015). A key issue is then the extent to which hardware firms rely on physical proximity versus activity organised at a distance: for example, in prototyping and in establishing supply chain and distributor relationships, as well as in core product development.

3.3/ Tech firm trajectories [to do]

[something about tech startups and how they typically develop]

4/ Case study background

This section of the paper briefly reviews the evolution of the ICT sector in Sweden. I draw heavily on Giertz (2015b) for this account.

4.1 / History

Sweden has a deep history of involvement in information and communication technology production. These can be traced back to the late 1800s; Sweden industrialised late compared to European rivals, but then developed very rapidly, particularly in telecoms: by 1855 there were 5,000 telephone sets in Stockholm, the highest in the world at that time. In the first half of the twentieth century, especially in the post-WW2 period, ICT industries developed through a corporatist national policy framework. Government took a strong interest in research and higher education, seeing engineering sciences as a national investment for the future. A key policy concept at this time was the notion of 'development couples', in which the state would act as the anchor client for a major private sector firm developing some technology / infrastructure of national importance. Examples include the national power grid (developed by Vattenfall and ASEA) and joint ventures into digital telecoms (PTT, Televerket and Ericsson). This model also applied to the country's computing efforts: the BARK and BESK machines developed by public sector in the 1940s and early 1950s were taken over by Saab in the late 1950s (through DataSaab).

Some of these industrial policy bets worked out better than others: the Swedish PC industry faded away in the 1980s, but the mobile communications industry did better. By 1969 a common Nordic mobile system had been developed; by 1985 the NMT was the world's largest mobile network. The pan-European GSM standards group was formed in 1982, with Swedish companies heavily involved in developing the standard for its eventual launch in 1991: it subsequently became a global benchmark for telecoms, helping establish Ericsson as a global ICT player.

The corporatist policy framework, already under political attack in the 1970s and 1980s, was rolled back substantively during the 1990s after a fiscal crisis, when a number of pro-competition and pro-entrepreneurship policies were also introduced [REF]. In 1995 Sweden joined the European Community and deregulated energy, telecoms, postal services and the media, rolling back the nationalised / corporatist economic development model. In 1993 Televerket was turned into Telia AB; split in joint ventures with Ericsson; Telia was partially privatised in 2000.

The early 2000s saw Ericsson, the country's largest ICT firm, enter a period of crisis. With over 100,000 employees worldwide, the firm had geared up for the rollout of 3G infrastructure networks. This market failed as many countries used auctions to allocate 3G licenses; operators spent heavily on licenses instead of Ericsson's products and services. The dotcom crash amplified the problem. By 2001 the company had moved out of handsets altogether, selling this division to Sony; by 2004 it had shrunk around half its workforce, with large job losses in Sweden. Today the company is a supplier of services more than a manufacturer; around 40% of the firm's revenue and 50% of its staff are involved with managing outsourced operations for ISPs (Giertz et al 2015).

Given Ericsson's dominant position in Sweden, these company-level shifts had important knock-on effects. Many laid-off engineers moved into hardware engineering, finance or banking, triggering a wave of entrepreneurship across ICT, especially software and the internet. As Giertz writes, these structural changes helped usher in ‘a radically different ICT sector’ that ‘differs significantly from a historically more traditional computer and telecommunications industry’ with well-defined hardware, software and systems management verticals. ‘Today, however, the [Swedish] ICT sector consists – even in a narrowly defined definition – of a variety of companies with completely different business logics and business focus.' [p106]

In parallel with these evolutions in ICT industry structure, public policymakers in Sweden introduced a number of measures to support new firm formation, in technology and other sectors. During the 1990s, government became increasingly aware that the country’s high levels of R&D activity were not translating into higher labour productivity or TFP. This ‘Swedish Paradox’ (Bitard et al., 2008; Chaminade et al., 2010; Giertz, 2015a) was put down to a national focus on basic research over commercialisation, and/or by the dominance of MNEs and lack of support for SMEs. A policy consensus gradually grew on the need to raise levels of entrepreneurship in the country, especially in high-value activity.

A number of subsequent reforms implemented in the 1990s and 2000s appear to have helped develop the country’s entrepreneurship culture (Semuels, 2017). Competition policy changes strengthened protections against anti-competitive behaviour and simplified the process of starting new firms; inheritance tax and some wealth taxes were removed, which may have helped increase angel funding; and a national programme provided subsidised PCs to households, with employers sharing costs; this widely diffused computers into society, including to households that otherwise would have been unable to afford them [I23].

Vinnova, the national innovation systems agency, was founded in 2001, as part of a major reorganisation of national economic development institutions; it operates alongside three more ‘traditional’ research councils as a ‘hands-on’ agency that brings together public and private actors [P17, P19]. It takes a major interest in Industry 4.0, aiming to connect traditional industry [ships, forestry, mining etc.] to new digital processes, and tools, especially in export industries.

5/ Quantitative analysis

What does the Swedish ICT sector look like today? Table 1 compares mean characteristics for the set of Industry 4.0 producing industries against the rest of the economy, pooled across 2007-2012. The right hand column gives the result of a two-tailed T-test on means. I compare across the key characteristics in Table 1, and also on the basis of STEM workforce 'intensity' and its component parts. This last borrows the concept of 'creative intensity' widely used in creative economy analysis (Higgs et al., 2008). This defines a set of 'creative occupations' and then looks at how 'intensively' these are used across different industries. For a given industry *i*, creative intensity is defined as (workers in creative occupations in *i* / all workers in *i*). Here, we substitute creative occupations for scientists, engineers, tech workers and the aggregate set of STEM workers.

Table 1 about here

We can see that in almost all key characteristics, including workforce mix, the science and tech industries differ from the rest-of-industry average. Notably, while these industries produce substantively more patents than the rest of Sweden (and cover over 75% of all Swedish patenting, see Table 2), and generate substantively higher exports, overall value added and turnover are not significantly different from other Swedish industries. This provides some support to the notion of the Swedish Paradox. We can also see that compared to non tech-industries, Swedish ICT has significantly more large firms, fewer startups and fewer SMEs.

Table 2 about here

Table 2 shows the main characteristics of the Swedish science/tech sector as mapped to Industry 4.0. The table covers the period 2007-2012 inclusive.

The top panel looks at workforce characteristics, the middle and bottom panels cover firm characteristics. For each panel, I show totals by year, percentage change over the period, and the these sectors' share of activity across all workers / all firms, accordingly. We can see that in 2012, the Swedish sci-tech sectors employed around 18% of all workers (top panel). Skilled workers make up a disproportionate share of this (these industries employ 21.6% of all graduates, and just under 30% of all workers with postgraduate qualifications). Not surprisingly, over 2/3 of the country's workers in STEM jobs are employed in the science and tech sectors. While these industries' overall workforce share has fallen slightly between 2007 and 2012, shares of skilled and STEM workers have risen, often substantially.

Sci-tech industries comprise just under 10% of all firms in Sweden (middle panel). The sector has grown by 17% since 2007 and its composition has changed, with a big rise in SMEs, a rise in startups and a fall in large firms (those with over 250 staff). Nevertheless, the sector still contributes over a fifth of all large firms in Sweden. In terms of broader economic performance (bottom panel), turnover, value added and exports are all on an upward trend – but strikingly, patenting, a key innovation measure, is down since 2007.

Giertz et al (2015a) provide further detail, classifying Swedish ICT firms into eight cross-sector verticals including hardware. However, they focus on a much narrower range of established ICT firms (2700 companies that have over five employees) compared with my sample. Within this smaller set, the 'hardware components' and 'complete systems' verticals comprise around 14% of firms and over 20% of all ICT sector staff (over 26,000 of 132K FTE in 2011, compared with 459k in my data).

As in my ICT-wide data, hardware activity is a mix of a few large incumbents, plus a long tail of SMEs. The complete systems vertical is dominated by a few large incumbents – with under 200 firms in total, of which Ericsson accounts for over 70% of all employees. By contrast, the hardware components vertical is dominated by SMEs, with around 10 employees on average; the few large firms have only a few hundred staff. Many of these firms are 'contracting manufacturing'. Many of the newer firms are startups producing 'fibre optics, nanotech, power electronics, printed electronics, control equipment, measuring and calibiation, antennas, power transistors, alarms, lasers, sensors and actuators', and many are connected to universities.

Giertz and co-authors are sceptical about the economic prospects of these startups and SMEs, the focus of this paper. They report that around half of the micro firms in this vertical are making a loss (and are often subsidised by VC and/or bootstrapping). While this is not unusual for young tech firms, the authors are pessimistic about the chances of hardware startups developing national importance:

> *'... it is hardly likely that they will be the foundation of a Swedish industry producing standard electronics in large volumes. That kind of mass production has probably moved to Asia to stay.' [p111]*

The other hardware-relevant component of the Swedish ICT industry is R&D focused consulting, which in Giertz et al comprised over 360 established firms and almost 12,400 staff in 2011. These firms work with other tech businesses on ‘pure technical applications’, including an important subset dealing with embedded systems and the Internet of Things. The roots of this consulting sector lie largely in the corporate shakeups discussed earlier in this section; as companies like Ericsson laid off staff, many moved to establish or work in firms such as these. As we shall see, these companies are an important source of expertise and support both for large industrial MNEs and the hardware tech startups.

5.2 / The Stockholm tech milieu

Swedish science and tech industries are highly clustered, with Stockholm city and county the largest agglomeration of activity. Tables 3 and 4 give counts, shares and location quotients at municipality level for the years 2007-2012.

Table 3 looks at the 20 municipalities with the largest counts of Industry 4.0 firms. Over a quarter of these are in Stockholm county, with Stockholm municipality having over twice as many firms as the next municipality (Gothenberg), over three times as many sci-tech SMEs and around twice as many employees in sci-tech industries. Notably, tech SMEs make up almost all of the population of ICT firms, and between 9 and 18% of all SMEs in these municipalities. Stockholm county comprises around 47% of all science/tech employment in the 20 most ICT-firm dense municipalities.

Table 3 about here

Counts and shares do not fully control for areas' underlying economic structure. Table 4 uses location quotients (LQs) to do this, for the 20 municipalities with the highest sci-tech firm LQs in 2007-2012. Lund has the highest LQ of sci-tech firms in Sweden in this period; Stockholm city has a rather lower LQ, reflecting its greater economic diversity. However, Stockholm county dominates the table: just under two-thirds of the Sweden's largest tech firm clusters are in Stockholm municipalities.

Table 4 about here

Other studies confirm this picture. Chaminade et al (2010) point to the Kista cluster of large tech MNEs (including Infosys, Huawei and Lenovo) just outside Stockholm city, as nationally important, alongside Skåne county (for computer games) and Linköping (for web servers). Over half the ICT employment identified by Giertz and colleagues (2015a) is located in Stockholm county[2] – over 60,000 FTE staff, far fewer than in Table 3 above given their very restrictive sampling frame. Six of the eight verticals identified have over half their employees in the area. In hardware systems, Giertz et al highlight that Ericsson has always been critically important to the Stockholm cluster – both through its location in Kista and elsewhere in the metro area, and through its system-wide effects across the county and the country as a whole. Notably, the two least concentrated sectors identified by Giertz et al are the focus of interest in this study. 77% of hardware components staff work outside Stockholm county, as do 65% of R&D-related consultancy staff. Stockholm remains the single largest location for these activities, however.

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[2] Stockholm county consists of 26 municipalities, out of 290 municipalities and 20 counties in the whole of Sweden. (https://en.wikipedia.org/wiki/List_of_municipalities_of_Sweden).

5/ Qualitative findings

This section summarises the qualitative research with two groups of firms (hence COWORKING and CITY), as well as stakeholders in the wider milieu / innovation system. I start by looking at firm founders; then company characteristics; then workspaces; then Stockholm; then the wider innovation system (universities, public agencies, industrial legacy and culture). In what follows firm interviews are prefixed F, policymakers P, industry intermediaries I.

5.1 / Founders

Founders in the COWORKING group of small / young firms were evenly split between those placing themselves as *'programmers' / 'coders'* and those identifying as *'business types'*, with a small number presenting as *'engineers'* or *'scientists'*. In the CITY group or more established firms, founders / senior staff were identified as *'business people'*, some with engineering backgrounds. A few people in both groups had more hybrid experience.

Founders typically operated in teams of two or more, often adding further senior salary roles / co-founders in the early stages. Typically business person often brought on as co-founder after technical development. Consistent with this, I was told that researcher-led teams in the hardware space often need a CEO with some business experience [I24]. In the COWORKING group, levels of experience varied hugely, from founders who were (literally) still at university to those with 20 years + in industry. For CITY firms, the majority of founders had 10 years or more industry experience.

5.2 / Firms

As discussed above, there is no fully common terminology to discuss the 'hardware tech' space. Stakeholders typically referred to 'hardware' firms, but acknowledged that this covers a range of products and services. Interviewees variously placed themselves as one or more of IOT/smart devices; drones; AI; software/ SaaS; medical/pharma; and consumer electronics. Of these, a handful were software / SaaS firms, where the application was industrial internet or consumer electronics hardware settings. All of those whose primary product was physical, also built software and/or apps. In both groups, the majority of firms positioned themselves as B2B, not B2C (latter = consumer electronics). A small number had developed technologies with multiple / general purpose applications (for example, low power radio chips; sensors; simulation platforms; OS / SaaS applications) and had selected a single application as a first route to scaling.

One CITY company was a classic example of the Swedish 'ICT consulting' firm (Giertz et al 2015), a mid-size firm which built and implemented hardware and software products and services, as well as packaging these into consultancy and fixed price projects [F14]. Historically it had worked as an *'external hub'* to Swedish MNEs, and smaller manufacturing firms; now it was increasingly working with Stockholm tech startups.

The majority of COWORKING and CITY firms were under five years old; in the second group, a couple were over 20 years old. In workforce terms, COWORKING firms were all small or microbusinesses; CITY firms were either small or in one case, medium-sized. Overall, interviewees were at an early revenue stage. Within this, there was a lot of variation: better-funded firms in both groups used a combination of VC/angel and Government grants/loans. The small number of B2C firms in both groups had also all used Kickstarter.

Many of the smallest / youngest COWORKING firms were pre-revenue (estimated at 50% [I22]. These firms financed themselves through various tools including bootstrapping (typically via consultancy), research grants, including some from Vinnova; Almi loans; and VC/angel funding. A few firms in the COWORKING group were already making significant sales revenue, despite their early overall growth stage. By contrast, the majority of CITY firms were already running on revenue, supplemented by bootstrapping, Kickstarter and VC funds. F15, in this group, was the only company to be pursuing exit through acquisition.

5.3 / Workflows

This sub-section looks at firms' geographies of operation. COWORKING firms were a majority of single plants, a minority with bases in other parts of Sweden (Linkoping, Karlskrona, Eijakstufil) and a few micro-multinationals (Varian, 2005) with individual employees in other countries. In rather more cases, firms had supply chains / value chains that stretched outside of Sweden (see below). In contrast, two CITY firms were based only in Stockholm, and three had multiple plants in Sweden, and one had multiple sites outside Sweden.

In line with existing research (Grabher and Ibert, 2014; Bathelt, 2005), firms in both groups commonly used remote working tools (Google Hangouts, Skype, Bluejeans) to link with staff and partners/suppliers in other locations, as well as rich social media tools as such Slack. These were typically complements to face to face working, often in highly sophisticated [idiosyncratic] configurations: CITY firm F13 described how in complex projects, face to face meetings were held by senior people and those with customer-facing roles, who are happy to meet others: they scoped out key people / established trust on behalf of those who did not travel.

Even for startups, hardware tech activity requires a conventional supply chain, unlike counterparts in services-focused parts of the tech industry. Interviewees' supply chain geographies were variable, with most making at least some use of the wealth of Swedish electrical engineering experience and expertise. However, the more generic the components/activity required and/or the bigger the volume, the more likely supply was offshored (first to Baltics, then to East Asian countries). A few firms in both groups actively tried to keep all manufacturing in Sweden, citing the need to use specialists; plug into expertise, networks, or knowledge; a business model majoring on quality; or the need for small / fast runs [e.g. F3, F8, F10, F12, F14] (see also Section 5.8). Many had found firms in the Baltic countries provided a good solution to the cost/quality/proximity tradeoff. Some CITY firms had used dev teams in e.g. Eastern Europe, but typically bring them in-house over time. Stakeholders [I22, I23, I24, I26] reinforced this picture, suggesting that hardware tech firms typically do prototyping and small scale manufacturing in Sweden; but go abroad for larger runs because of a combination of lower costs, and seeking out experienced suppliers who can provide (tacit) knowledge on organisation, standards and governance of larger-scale manufacturing.

Across the sample, firms shared a desire to export, agreeing that Sweden was too small a market to scale in. Echoing the common view, Sweden was seen as ‘a nation of early adopters’, good for testing out new products, but with lots of competition from other firms. COWORKING firms were typically focused on selling in Baltic / Nordic countries before moving on to larger international markets; CITY firms were focused on Europe and/or the US.

5.4 / Workspaces

The COWORKING firms all used the same shared workspace; 3/5 CITY firms also used co-working spaces, although these were significantly different in nature (see below).

The COWORKING space was run by a Stockholm accelerator programme in collaboration with one of the city’s universities. As with many other such incubator spaces, the building provided a mix of input-sharing, partnering opportunities (matching) and knowledge spillovers (learning), with tenant firms paying a rolling rent at a low price point (What Works Centre for Local Economic Growth, 2017). However, given the Industry 4.0 setting, the configuration and emphasis was rather different from a conventional tech incubator. It provided access to expensive specialised equipment such as 3D printers, laser cutters, drills and soldering rigs, as well as the potential to access university scientific infrastructure. It also provided firms with access to senior industry figures and larger electronics / engineering firms / MNEs such as ABB, Ericsson and Vattenfall (via meetups and pitch sessions, with mentors recruited through a ‘partners’ programme (which also helped fund the space). A core group of six MNE representatives met quarterly and developed ideas on how to work more effectively with startups, outside conventional procurement and M&A [I26].

Stakeholders agreed that the COWORKING community was the space’s most important feature, but took different views on the key dynamics. Some suggested that informal peer-peer collaboration between tenant firms was the most important feature [I22]. Others [I26] argued that the SME-MNE links were the most important, given the structural and local challenges facing startups in the hardware space, and larger firms' need to better connect with local startups (see sections 5.8 and 6 below).

From firms' point of view, the space had a number of affordances. These included a positive atmosphere, which helped signal seriousness of purpose to potential customers and investors: the slightly *'rough + ready'* / boiler suit vibe was thought to actually help the messaging, vs. a more corporate space that didn't fit the product set. Notably, given stakeholders' emphasis on matching and learning economies, firms suggested that input-sharing was a big advantage of the space – having access to equipment, and to university students and staff members (as interns, RAs and in some cases, staff). Many firms went to the meetups organised by the workspace managers. Peer networking was felt to be less important.

Firms could only identify a few concrete downsides (the rent could be lower, the building could be a bit smarter, it would be nice to have X piece of specialised equipment). The biggest issue raised was the low numbers of tenant firms, and more specifically, the lack of critical mass in any one hardware vertical. Tenant firms wanted more firms like them in the 'hardware space', to facilitate learning. Firms were quick to point out that this also reflected characteristics of the Stockholm hardware cluster and even the national economy: for example, at the time of writing there were only five drone companies in Sweden, most of which worked in military applications cloaked in secrecy. This lack of critical mass also reflects deeper structural challenges in developing hardware products/services in a startup setting (see Section 6).

The majority of CITY firms also used co-working spaces. In one case this was a fairly cheap co-working building close in feel to the COWORKING group; the two other cases had chosen a *'professional' / 'mature'* space which provided *'the right appearance'* to clients who might visit. All emphasised that their choices were driven by cost and flexibility, rather than any desire to network with other firms in the space – it was felt that had *'done that'* and wanted to focus on building the firm. This exclusive focus on input-sharing contrasts with the more complex motivations of the COWORKING group.

5.5 / Stockholm

Why had firms chosen Stockholm? The city was commonly described – by firms and stakeholders – as the engine of the national economy, with a critical mass of economic activity (upstream and downstream markets) and industrial diversity, plus supportive institutions, that firms could draw on. Firms also acknowledged the local legacy of Ericsson, especially the early C21 wave of layoffs that helped diffuse knowledge into the area (see Section 4, also sections 5.8 and 6). One stakeholder [I25] also linked the city's urbanised tech scene to the shift of Silicon Valley tech firms from the South Bay into San Francisco. The main city-level drawbacks mentioned were cost of living, lack of housing [cited explicitly by a couple of firms], and the difficulty of finding skilled people since *'Spotify just sucks [in] everybody'* [F15].

Consistent with the quantitative evidence in Section 4, interviewees agreed that the city / metro area had a large tech cluster, and that it was in a growth spurt – 'Stockholm is exploding with startups at the moment' [I24] with more firms and more outside finance, especially from the US arriving the last five years. The huge popularity of startup working in Sweden as a lifestyle choice has helped drive up the number of startups [I24]. However, stakeholders also characterised this as a shift to *'growth and maturity'* [I23], with some major local players – such as Spotify, Mojang, King – now over 10 years old. As with Ericsson before them, there is now a local 'community' around these companies. Some staff who came to work for one of these big firms have left, and set up their own companies; others talk about their experience in meetups, or advise others. In turn, this has helped learned 'competence' spread across the cluster. These mature firms have also helped draw larger VC funds to the city in recent years.

For hardware specifically, interviewees cited both individual success cases and more structural factors. iZettle, originally a card reader firm, showed that hardware firms could break through [I24]; there was also a *'pendulum swing'* from software to hardware, as more and more founders recognised the potential to draw on Swedish depth of expertise [F13].

Overall, both COWORKING and CITY firms were positive but a bit grudging about hardware's place in the cluster. The tech scene was seen as built on music; fintech; web, and other B2C products. There were a range of view on how connected hardware firms were to the wider ‘community’, and thus what firms could learn from the bigger set of tech companies in the area. One mentioned that *‘it is very easy to just pick up the phone and be very honest about the situation. And they will be quite happy to help you, and interested in what you are doing’* [F10]; another that *‘we learnt more in two weeks in Palo Alto than two years in Sweden’* [F1].

It was striking how little the firms wanted to network. The general view was that you network in the early stages, then get focused: *‘they do serve a purpose, these informal tech meet-up kind of scene things. And it’s especially good if you’re starting out; if you’re a really young start-up and you’re kind of feeling your way’* [F16] was a typical response. There was some scepticism about the inherent value of meetups, or founders’ capacity to network effectively: *‘to be honest, we are not the networking persons either. We don’t enjoy that environment, we don’t… we have tried to find a third partner who perhaps has those skills, but we just haven’t found it.’* [F15] … although at least one interviewee had met a future co-founder at one. There was also some scepticism that much of the cluster consisted of some kind of lifestyle business: one told us that there *were 'two types of tech firms in the city: Three tech guys who do everything themselves, or three business people with an idea but no idea how to do it’* [F13]. Interviewees seemed to see themselves as more serious (and more hardworking) than ‘softer’ tech ventures.

This standoffishness seemed to reflect both cultural / attitudinal factors and hardware firms’ tougher development paths. On finance, the common view was that it was very hard to get funding compared with e.g. consumer-focused software firms. Angels and VCs (in particular) were seen as preferring software – they understood the space better, it was seen as less risky and with faster exits. One interviewee argued that private sector VC firms were *‘a bit scared of hardware’* [I26]. Notably, no 100% hardware focused VC firms operating in Sweden [I23]. But this reflects the bigger, structural issue that there actually aren't that many hardware-specialised VC firms in the world.

Notably few interviewees had much direct contact with Kista, despite the presence of many world-leading MNEs there, including Ericsson’s HQ. The area was acknowledged as *'Ericsson country'*, and interviewees also cited the KTH campus, STING accelerator, and various networking and collaboration programmes. One interviewee had relocated into Stockholm from Kista, mainly for the city’s amenity offer and its impact on recruitment: in Kista *'youngsters complained there was nothing to do in the evenings'* [I25]. Another pointed out that for hardware, most of the relevant university departments were downtown in Stockholm.

5.6 / Universities

COWORKING firms had close links with the space’s host university (some founders were ex-students, one founder was a current student). The university also acted as a supplier of employees and interns; of equipment; expertise; and business support (through the TTO, which was highly regarded by the minority who used it). At least two of the 11 firms interviewed were university spinouts. In contrast, the five CITY firms had little or no direct interaction with Stockholm’s universities, except through hiring graduates of those institutions.

Despite this on-the-ground complexity, stakeholders all suggested that universities were ‘fundamental’ [I23] to the success of the cluster. KTH, Stockholm University, and the Karolinska Institute were the most commonly mentioned. I24 argued that the hardware cluster was substantively driven by KTH, which possessed a critical mass of knowledge and experience in electrical engineering.

5.7 / Public agencies

A number of firms had had interactions with Vinnova and Almi. Views on these agencies were heavily coloured by whether firms had received funding. There was some scepticism about Vinnova, which appears to be more selective: it was seen as too remote; overly focused on academic researchers and large established firms; and not interactive enough, *'just a big bag of money'* [I22]. In contrast, there were generally positive views of Almi, which had provided loan finance to several interviewees. Public sector funding was seen as supporting basic R&D, but crucially, not downstream commercialisation [I22].

More broadly, COWORKING firms had mixed views on public policy for hardware and for tech more generally; CITY firms were more positive overall, citing for example *'a general climate supportive of entrepreneurship'* [F16]. This suggests many of the pro-entrepreneurship national initiatives undertaken in the 2000s had borne fruit (see Section 4).

5.8 / Industrial legacy

The majority of firms in both groups sited themselves in a larger tradition of Swedish electronic engineering and hardware expertise. Some argued that their products (such as smart objects; energy systems; tools for industry) were an extension of this industrial history. Others, especially in the COWORKING group, drew more direct connections, citing parents' jobs in Ericsson, growing up around these prominent national champions, taking pride in this and wanting to honour it.

Stakeholders took a similar line, stressing the importance of history and the role of path-dependence. Sweden has a great history of manufacturing firms in the past 150 years; hardware tech is an opportunity to develop a new generation of national players [I22]. MNEs form the *'roots'* of the cluster, which are still seen as active in the *'deep background'* [I23]. Ericsson, in particular, has been hugely important for the cluster through its accumulated knowledge, both in its interactions with other firms in the national economy; through workforce mobility; and through periodic periodic layoffs, all of which diffuse this knowledge into the wider economy.

The majority of firms, all SMEs, saw these larger firms and ecosystem knowledge as a set of assets to plug into; through supply chain relationships; collaborations; and through hiring staff. One firm *mentioned 'our chief builder is 69, he used to make helicopters'* [F11]; another used an East Asian factory founded by a former Swedish factory owner who had relocated, but retained close links with the country [F16].

However, stakeholders felt that SMEs’ links with larger Swedish companies could and should be improved. The dominant Swedish electrical engineering firms had, over time, developed closed R&D systems and were seen as slow to understand and make use of new ideas emerging out of the growing startup space. In some cases, actors had developed platforms to link startups and incumbents in a many-to-many setting [I22, I25, I26]. In other cases, MNEs had developed one-to-many responses such as corporate accelerators, linking a number of startups to a single large corporation [I22].

5.9 / Culture

A few firms in both groups raised issues around Swedish culture, both positive and negative. Some of the non-Swedish-born founders felt that ‘Swedish culture’ did not involve much sociability outside immediate family and existing friends, with relatively low openness. However, others emphasised the open and helpful nature of all actors in the local hardware scene. Those who raised cultural issues also flagged perceived Swedish liking for ‘order and rules’; this was seen as helpful inasmuch as it led to more active public policy to guide new companies into growth paths.

6/ Discussion

This paper is a mixed methods exploration of the ‘hardware tech’ cluster in Stockholm. Hardware tech firms – typically startups or SMEs – combine software and programming expertise with a physical product / service. These firms sit within the Industry 4.0 technology-industry-product space: as distinctive small producers, and as hybrids operating outside established ‘tech’ settings such as web services. We can view these firms as a distinctively Swedish phenomenon with roots in the country’s deep history of electrical engineering, and the clustering of large industry players, especially Ericsson, in the Stockholm metro area. But we can also see them as the products of recent national and city-level policy pushes to promote entrepreneurship and US-style startup culture.

Industry 4.0 arguably represents part of a larger technological systems transition, with a rapidly growing set of technological, product and service recombinations (Kremer 1993, Perez 2010). Startups at the technological frontier may thus represent one important source of national future competitive advantage. Swedish hardware firms can draw on unique national/local resources and strengths – but also face significant obstacles in taking small-run, complex products and services to scale.

Many of these challenges are structural, and seem to be inherent to startups in the hardware space as defined above. A first issue is technological complexity. Hardware firms require skills in all of programming, electronics and manufacturing, as well as business development: *'you need more than one brain'* to do hardware [I26]. In turn, this typically requires bigger founding teams, and adding further key roles later on; the need to buy or get access to specialist inputs and equipment; and longer initial development time.

Second, the role of physical products generates additional development challenges and risks: in prototyping; building supply chains, downstream distribution and logistics systems; meeting official standards and certification; managing the defect and return cycle.

A third issue is that conventional startup finance providers have notably less interest in and knowledge of hardware than software. The finance Catch-22 is that investors see hardware as requiring more resources, but generating slower and riskier returns; fewer firms develop to scale; fewer funds from firm growth are ploughed back into new hardware startups, and fewer successful founders apply their knowledge to help new businesses in the space.

As a result, young hardware tech firms are typically on slower growth trajectories than (say) software or web services counterparts; and more focused on growing through customers / revenue than through external finance. As newer, smaller firms, COWORKING firms faced strong versions of all these challenges. CITY companies, who had typically found some external finance, were more concerned with raising larger rounds, and/or finding the right staff.

Taken together, these challenges suggest substantive structural obstacles in applying classical US startup culture to advanced manufacturing settings, a view shared – at least in part – by the majority of policymakers and industry observers interviewed. A pessimistic take is that *'these firms will never be big'* [I26], supporting the equally pessimistic view of Giertz and colleagues (2015a) that *'... it is hardly likely that [these firms] will be the foundation of a Swedish industry producing standard electronics in large volumes.'*

However, this research also uncovers other potential growth paths for Swedish hardware tech startups to fulfil their full potential. One avenue may lie in focusing on high-growth niches; although given firms' universal interest in export-led growth this may some re-adjustment of expectations and strategies. Further growth paths may also lie in stronger supply chain linkages, collaborations and/or acquisitions with the country's world-leading electrical engineering MNEs. The research suggests opportunities for better connections between large incumbents, with financial resources and the ability to leverage economies of scale, and smaller / younger firms on the technological frontier.

However, Sweden's legacy of large engineering firms also turns out to present challenges, as well as opportunities. For example, historically, Sweden has not had a big mergers and acquisitions culture. The lack of specialist domestic angel and venture finance has led many hardware firms to look overseas for development funding, so that ownership / control transfers at least partially outside the country [I22]. The dominant electrical engineering firms have tended to focus on excellence in incremental innovation rather than disrupting core business models, in the way that many startups offer [I22, I25]. Firms have also been used to owning and controlling IP [I26], and this presents further issues in designing, setting and enforcing contracts in joint venture settings.

State actors have a series of important innovation and industrial policy roles to play here. Endogenous growth frameworks (Romer, 1994) and innovation systems frameworks (Freeman, 1991) all emphasise the role of the public sector in co-creating innovative activity, and in de-risking entrepreneurship. More 'entrepreneurial state' thinkers (Black and Keller 2008, Mazzucato 2015) emphasise the 'visionary' developmental role of the State in encouraging strategic and/or frontier technologies and sectors.

Sweden’s national innovation policy agenda already takes an active role in funding research, loan finance, and broader public-private innovation ecosystem development. However, this research has uncovered some gaps in policy attention on a potentially nationally important strategic set of Industry 4.0-related technologies, sectors and products. There were some encouraging signs of local policy innovation, which might bridge the substantive cultural and co-ordination problems highlighted here. These included many-to-many industry networks that linked MNEs and SMEs; corporate accelerators; and network-focused co-working spaces. Issues that are likely to require further policy effort include information and awareness-raising around existing resources; public and/or public-private finance instruments, beyond R&D tools; and helping SMEs scale by accessing high quality local and international supply chains and distribution systems.

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Tables

Table 1. Science/tech industries in Sweden: distinctiveness.

Variable	Science/tech sector	Rest	Different?
Total employment	4,395.439	4,209.906	N
Number of tertiary ed employees ≤ 3yrs	826.717	636.933	Y
Number of tertiary ed employees > 3yrs	1,396.159	783.519	Y
Total STEM workers	954.285	250.847	Y
Average science workforce intensity	0.013	0.010	Y
Average engineering workforce intensity	0.015	0.006	Y
Average tech workforce intensity	0.037	0.013	Y
Average stem workforce intensity	0.065	0.029	Y
Total firms 5 years old or less	273.221	420.884	Y
Total large firms	2.161	1.628	Y
Total SMEs	882.073	1,582.661	Y
Total value added (mSEK)	3,579.333	3,211.102	N
Total net turnover (mSEK)	13,017.630	11,681.930	N
Total exports value (mSEK)	4,181.818	1,694.266	Y
Total patents weighted by applicants	13.830	3.012	Y

Source: Statistics Sweden
Notes: graduates are those with 3 years or less tertiary education; + postgrads adds in those with more than 3 years tertiary education; STEM occupations defined from NESTA (2015); Intensity = share of workers in science / engineering / tech / stem occupations, compared to all workers in these industries; Tech industries defined using ONS / Harris (2015); Turnover, value, added, exports value given in mSEK; Patents weighted by applicants. Difference = two-tailed t-test, 5% significance or better.

Table 2. Science/tech industries in Sweden: performance.

	Workers	Graduates	+ Postgrads	STEM workers
2007	464,683	85,516	135,288	90,503
2008	476,401	86,365	141,980	97,519
2009	455,653	84,132	143,814	99,395
2010	445,812	85,646	147,129	100,925
2011	459,503	88,853	153,370	104,161
2012	462,679	89,493	156,603	107,742
% change 2007-12	*-0.43%*	*4.65%*	*15.76%*	*19.05%*
% all, 2012	*17.73%*	*21.62%*	*29.97%*	*67.02%*
	Firms	**Startups**	**SMEs**	**Large firms**
2007	87,425	27,923	86,726	238
2008	90,552	28,274	89,483	237
2009	92,683	28,439	91,395	225
2010	87,493	27,415	85,912	221
2011	101,718	30,102	100,265	218
2012	102,606	29,703	101,043	220
% change 2007-12	*17.36%*	*6.37%*	*16.51%*	*-7.56%*
% all, 2012	*9.68%*	*11.40%*	*9.67%*	*22.00%*
	Turnover	**Value added**	**Exports**	**Patents**
2007	390,990	1,394,861	443,986	1,767
2008	376,374	1,427,239	459,208	1,690
2009	319,548	1,191,571	356,198	1,504
2010	381,274	1,260,775	410,137	1,677
2011	400,075	1,465,458	495,151	1,518
2012	383,141	1,448,182	465,684	
% change 2007-12	*-2.01%*	*3.82%*	*4.89%*	*-14.04%**
% all, 2012	*19.57%*	*18.67%*	*45.57%*	*76.93%**

Source: Statistics Sweden
Notes: Tech industries defined using ONS / Harris (2015); graduates are those with 3 years or less tertiary education; + postgrads adds in those with more than 3 years tertiary education; STEM occupations defined from NESTA (2015); startups defined as firms 5 years old or less; Turnover, value, added, exports value given in mSEK; Patents weighted by applicants; * change and national shares given for 2011.

Table 3. Sci-tech firms and workers, top 20 Swedish municipalities by firm counts, 2007-2012.

Code	Municipality	County	Sci-tech firms		Sci-tech SMEs			Sci-tech workers	
			Total	% all firms	Total	% all SMEs	% all tech	Total	% all workers
0180	Stockholm	Stockholm	17176	13.84	17114	14.04	99.64	121529	17.32
1480	Göteborg	Västra Götaland	6881	14.32	6853	14.51	99.59	64989	32.93
1280	Malmö	Skåne	3096	12.22	3091	12.46	99.84	12496	14.21
0380	Uppsala	Uppsala	2353	13.43	2351	13.64	99.92	6932	21.19
1281	Lund	Skåne	1854	17.90	1850	18.12	99.78	11685	41.25
0580	Linköping	Östergötland	1531	13.83	1529	14.09	99.87	13039	42.65
1980	Västerås	Västmanland	1337	14.11	1332	14.31	99.63	15099	41.55
0182	Nacka	Stockholm	1281	13.82	1279	14.03	99.84	2544	19.59
1283	Helsingborg	Skåne	1231	10.84	1230	11.05	99.92	4202	12.77
0160	Täby	Stockholm	1214	16.95	1214	17.23	100.00	1978	14.70
2480	Umeå	Västerbotten	1030	9.60	1029	9.70	99.90	2042	10.83
0184	Solna	Stockholm	1026	15.74	1022	16.02	99.61	4946	6.19
0163	Sollentuna	Stockholm	1014	17.35	1014	17.63	100.00	1855	11.13
0680	Jönköping	Jönköping	984	9.28	979	9.40	99.49	6291	22.05
0581	Norrköping	Östergötland	948	10.52	946	10.70	99.79	2908	10.33
1880	Örebro	Örebro	889	8.50	888	8.64	99.89	3557	10.67
1384	Kungsbacka	Halland	888	11.43	887	11.59	99.89	1146	12.19
0126	Huddinge	Stockholm	878	12.14	878	12.33	100.00	874	7.42
1490	Borås	Västra Götaland	797	9.01	795	9.12	99.75	4040	17.25
1780	Karlstad	Värmland	783	9.92	782	10.07	99.87	2384	13.57

Source: Statistics Sweden
Notes: tech industries defined using ONS / Harris (2015); startups defined as firms 5 years old or less.

Table 4. Sci-tech location quotients, top 20 Swedish municipalities by firm counts, 2007-2012.

Code	Municipality	County	Firms	SMEs	Startups	Employees
1281	Lund	Skåne	1.856	10.370	10.187	2.256
0163	Sollentuna	Stockholm	1.802	10.385	10.954	0.608
0160	Täby	Stockholm	1.758	10.386	10.395	0.802
0184	Solna	Stockholm	1.632	10.349	10.447	0.346
1262	Lomma	Skåne	1.603	10.392	9.925	0.984
1481	Mölndal	Västra Götaland	1.601	10.378	9.214	1.054
0183	Sundbyberg	Stockholm	1.571	10.377	11.006	0.688
0123	Järfälla	Stockholm	1.561	10.384	10.796	0.854
1402	Partille	Västra Götaland	1.507	10.392	9.647	0.693
0186	Lidingö	Stockholm	1.485	10.366	10.224	1.588
1480	Göteborg	Västra Götaland	1.484	10.349	10.554	1.793
0162	Danderyd	Stockholm	1.467	10.366	10.025	0.949
1980	Västerås	Västmanland	1.462	10.356	11.426	2.264
0180	Stockholm	Stockholm	1.435	10.354	10.836	0.944
0580	Linköping	Östergötland	1.433	10.375	10.489	2.324
0187	Vaxholm	Stockholm	1.432	10.392	10.923	0.532
0182	Nacka	Stockholm	1.432	10.382	10.687	1.067
0199			1.415	10.392	16.330	0.934
0117	Österåker	Stockholm	1.410	10.392	10.343	0.578
0128	Salem	Stockholm	1.403	10.392	10.122	0.382

Source: Statistics Sweden

Notes: tech industries defined using ONS / Harris (2015); startups defined as firms 5 years old or less.

Online Appendix

Table A1. List of sci-tech industries

'Science and tech' industries are drawn from an international benchmarking exercise conducted by the UK Office of National Statistics (Harris, 2015). The ONS set of industries is defined at 5-digit SIC2007 level. I refine this to focus on Industry 4.0, dropping a number of content activities (publishing, media, music, advertising) and science /health activities (life sciences, health) except where SIC descriptors directly pertain to R&D and/or manufacturing. We then crosswalk this to 4-digit SIC, which is identical to the NACE Rev 2 /SNI07 codes used in Sweden and other EU states.

NACE	NACE_descriptor	ONS_category
1920	Mineral oil refining	other science_tech manufacture
2000	Manufacture of chemicals and chemical products	other science_tech manufacture
2010	Manufacture of basic chemicals, fertilisers and nitrogen compounds, plastics and synthetic rubber in primary forms	other science_tech manufacture
2011	Manufacture of industrial gases	other science_tech manufacture
2012	Manufacture of dyes and pigments	other science_tech manufacture
2013	Manufacture of other inorganic basic chemicals	other science_tech manufacture
2014	Manufacture of other organic basic chemicals	other science_tech manufacture
2015	Manufacture of fertilisers and nitrogen compounds	other science_tech manufacture
2016	Manufacture of plastics in primary forms	other science_tech manufacture
2017	Manufacture of synthetic rubber in primary forms	other science_tech manufacture
2020	Manufacture of pesticides and other agrochemical products	other science_tech manufacture
2030	Manufacture of paints, varnishes and similar coatings, mastics and sealants	other science_tech manufacture
2040	Manufacture of soap and detergents, cleaning and polishing preparations, perfumes and toilet preparations	other science_tech manufacture
2041	Manufacture of cleaning and polishing preparations	other science_tech manufacture
2042	Manufacture of perfumes and toilet preparations	other science_tech manufacture
2050	Manufacture of other chemical products	other science_tech manufacture

2051	Manufacture of explosives	other science_tech manufacture
2052	Manufacture of glues	other science_tech manufacture
2053	Manufacture of essential oils	other science_tech manufacture
2059	Manufacture of other chemical products n.e.c.	other science_tech manufacture
2060	Manufacture of man-made fibres	other science_tech manufacture
2521	Manufacture of central heating radiators and boilers	other science_tech manufacture
2530	Manufacture of steam generators, except central heating hot water boilers	other science_tech manufacture
2540	Manufacture of weapons and ammunition	other science_tech manufacture
2610	Manufacture of electronic components and boards	digital technologies
2611	Manufacture of electronic components	digital technologies
2612	Manufacture of loaded electronic boards	digital technologies
2620	Manufacture of computers and peripheral equipment	digital technologies
2630	Manufacture of communication equipment (other than telegraph and telephone apparatus and equipment)	publishing and broadcasting
2640	Manufacture of consumer electronics	digital technologies
2651	Manufacture of non-electronic instruments and appliances for measuring, testing and navigation, except industrial process control equipment	other science_tech manufacture
2652	Manufacture of watches and clocks	other science_tech manufacture
2660	Manufacture of irradiation, electromedical and electrotherapeutic equipment	life science and healthcare
2670	Manufacture of photographic and cinematographic equipment	publishing and broadcasting
2680	Manufacture of magnetic and optical media	digital technologies
2700	Manufacture of electrical equipment	other science_tech manufacture
2710	Manufacture of electric motors, generators, transformers and electricity distribution and control apparatus	other science_tech manufacture
2711	Manufacture of electric motors, generators and transformers	other science_tech manufacture
2712	Manufacture of electricity distribution and control apparatus	other science_tech manufacture
2720	Manufacture of batteries and accumulators	other science_tech manufacture
2730	Manufacture of wiring and wiring devices	other science_tech manufacture
2731	Manufacture of fibre optic cables	other science_tech manufacture
2732	Manufacture of other electronic and electric wires and cables	other science_tech manufacture

2733	Manufacture of wiring devices	other science_tech manufacture
2740	Manufacture of electric lighting equipment	other science_tech manufacture
2750	Manufacture of domestic appliances	other science_tech manufacture
2751	Manufacture of electric domestic appliances	other science_tech manufacture
2752	Manufacture of non-electric domestic appliances	other science_tech manufacture
2790	Manufacture of other electrical equipment	other science_tech manufacture
2810	Manufacture of general purpose machinery	other science_tech manufacture
2811	Manufacture of engines and turbines, except aircraft, vehicle and cycle engines	other science_tech manufacture
2812	Manufacture of fluid power equipment	other science_tech manufacture
2813	Manufacture of compressors	other science_tech manufacture
2814	Manufacture of other taps and valves	other science_tech manufacture
2815	Manufacture of bearings, gears, gearing and driving elements	other science_tech manufacture
2821	Manufacture of ovens, furnaces and furnace burners	other science_tech manufacture
2822	Manufacture of lifting and handling equipment	other science_tech manufacture
2823	Manufacture of office machinery and equipment (except computers and peripheral equipment)	other science_tech manufacture
2824	Manufacture of power-driven hand tools	other science_tech manufacture
2825	Manufacture of non-domestic cooling and ventilation equipment	other science_tech manufacture
2829	Manufacture of other general-purpose machinery n.e.c.	other science_tech manufacture
2830	Manufacture of agricultural and forestry machinery	other science_tech manufacture
2840	Manufacture of metal forming machinery and machine tools	other science_tech manufacture
2841	Manufacture of metal forming machinery	other science_tech manufacture
2849	Manufacture of other machine tools	other science_tech manufacture
2890	Manufacture of other special-purpose machinery	other science_tech manufacture
2891	Manufacture of machinery for metallurgy	other science_tech manufacture
2892	Manufacture of machinery for mining, quarrying and construction	other science_tech manufacture
2893	Manufacture of machinery for food, beverage and tobacco processing	other science_tech manufacture
2894	Manufacture of machinery for textile, apparel and leather production	other science_tech manufacture
2895	Manufacture of machinery for paper and paperboard production	other science_tech manufacture
2896	Manufacture of plastics and rubber machinery	other science_tech manufacture

2899	Manufacture of other special-purpose machinery n.e.c.	other science_tech manufacture
2900	Manufacture of motor vehicles, trailers and semi-trailers	other science_tech manufacture
2910	Manufacture of motor vehicles	other science_tech manufacture
2920	Manufacture of bodies (coachwork) for motor vehicles (except caravans)	other science_tech manufacture
2930	Manufacture of parts and accessories for motor vehicles	other science_tech manufacture
2931	Manufacture of electrical and electronic equipment for motor vehicles	other science_tech manufacture
2932	Manufacture of other parts and accessories for motor vehicles	other science_tech manufacture
3000	Manufacture of other transport equipment	other science_tech manufacture
3010	Building of ships and boats	other science_tech manufacture
3011	Building of ships and floating structures	other science_tech manufacture
3012	Building of pleasure and sporting boats	other science_tech manufacture
3020	Manufacture of railway locomotives and rolling stock	other science_tech manufacture
3030	Manufacture of air and spacecraft and related machinery	other science_tech manufacture
3040	Manufacture of military fighting vehicles	other science_tech manufacture
3090	Manufacture of transport equipment n.e.c.	other science_tech manufacture
3091	Manufacture of motorcycles	other science_tech manufacture
3092	Manufacture of bicycles and invalid carriages	other science_tech manufacture
3099	Manufacture of other transport equipment n.e.c.	other science_tech manufacture
3212	Manufacture of jewellery and related articles	other science_tech manufacture
3240	Manufacture of professional and arcade games and toys	other science_tech manufacture
3250	Manufacture of medical and dental instruments and supplies	life science and healthcare
3312	Repair of machinery	other science_tech manufacture
3313	Repair of electronic and optical equipment	digital technologies
3314	Repair of electrical equipment	other science_tech manufacture
3315	Repair and maintenance of ships and boats	other science_tech manufacture
3316	Repair and maintenance of aircraft and spacecraft	other science_tech manufacture
3317	Repair and maintenance of other transport equipment	other science_tech manufacture
5100	Air transport	other science_tech services
5110	Scheduled passenger air transport	other science_tech services

5120	Freight air transport and space transport	other science_tech services
5121	Freight air transport	other science_tech services
5122	Space transport	other science_tech services
5820	Software publishing	digital technologies
5821	Publishing of computer games	digital technologies
5829	Other software publishing	digital technologies
6200	Computer programming, consultancy and related activities	digital technologies
6201	Computer programming activities	digital technologies
6202	Computer consultancy activities	digital technologies
6203	Computer facilities management activities	digital technologies
6209	Other information technology and computed service activities	digital technologies
6310	Data processing, hosting and related activities; web portals	digital technologies
6311	Data processing, hosting and related activities	digital technologies
6312	Web portals	digital technologies
7100	Architectural and engineering activities; technical testing and analysis	other science_tech services
7110	Architectural and engineering activities and related technical consultancy	other science_tech services
7111	Architectural activities	other science_tech services
7112	Engineering activities and related technical consultancy	other science_tech services
7120	Technical testing and analysis	other science_tech services
7219	Other research and experimental development on natural sciences and engineering	other science_tech services
7220	Research and experimental development on social sciences and humanities	other science_tech services
7490	Quantity surveying activities	other science_tech services
8540	Higher education	other science_tech services
8541	Post-secondary non-tertiary education	other science_tech services
8542	Tertiary education	other science_tech services
9511	Repair of computers and peripheral equipment	digital technologies
9521	Repair of consumer electronics	other science_tech manufacture
9522	Repair of household appliances and home and garden equipment	other science_tech manufacture
9525	Repair of watches, clocks and jewellery	other science_tech manufacture

Table A2. List of STEM occupations

STEM occupations are taken from NESTA (Bakhshi et al., 2015). I crosswalk these from UK SOC2010 occupation codes to SOC2008, then to the international ISCO08 and ISCO88 standards. The latter is identical to the SSYK-96 codes used in the Swedish data.

Category	ISCO88	ISCO88_descriptor
IT	1226	Production and Operations Department Managers in Transport, Storage and Communications
IT	1236	Computing Services Department Managers
IT	1316	General Managers in Transport, Storage and Communications
IT	1317	General Managers of Business Services
Science	2113	Chemists
Science	2211	Biologists, Botanists, Zoologists and Related Professionals
Science	2212	Pharmacologists, Pathologists and Related Professionals
Science	2111	Physicists and astronomers
Science	2114	Geologists and geophysicists
Science	2211	Biologists, Botanists, Zoologists and Related Professionals
Science	2212	Pharmacologists, Pathologists and Related Professionals
Engineering	2142	Civil engineers
Engineering	2144	Mechanical engineers
Engineering	2143	Electrical Engineers
Engineering	2144	Electronics and Telecommunications Engineers
Engineering	2149	Architects, Engineers and Related Professionals Not Elsewhere Classified
Engineering	2149	Architects, Engineers and Related Professionals NEC
Engineering	2150	Architects, Engineers and Related Professionals NEC
IT	2131	Computer Systems Designers and Analysts
IT	2132	Computer Programmers
IT	2139	Computing Professionals NEC
IT	2131	Computer Systems Designers and Analysts
IT	2132	Computer Systems Designers and Analysts
IT	2131	Computer Systems Designers and Analysts
IT	2132	Computer Programmers
IT	2139	Computing Professionals NEC
IT	2131	Computer Systems Designers and Analysts
IT	2132	Computer Programmers
IT	2139	Computing Professionals NEC
Science	2211	Biologists, Botanists, Zoologists and Related Professionals
Science	2212	Biologists, Botanists, Zoologists and Related Professionals
Science	1237	Research and Development Department Managers
Science	1319	General Managers NEC
Engineering	2148	Cartographers and Surveyors