‘HARDWARE IS HARD’: MANUFACTURING STARTUPS IN AN URBAN TECHNOLOGY CLUSTER

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Abstract

Studies of technology systems – like Industry 4.0 – pay surprisingly little attention to geography, despite localised knowledge spillovers’ role in innovation. Although tech entrepreneurship is associated with dense clusters, this may differ for physical ‘hardware’ activities. I explore these issues through a case study of hardware startups in Stockholm, a leading European tech hub. I uncover a growing milieu with much economic potential. However, cluster affordances are limited, with little peer learning and early-stage partners located across Sweden. This, plus product complexity and sparse angel/VC funding, put most startups on slower, revenue/grant/loan-driven pathways than software-focused counterparts. I outline high-level policy responses.

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

1/ Introduction

The ‘Fourth Industrial Revolution’ (OECD, 2017; Schwab, 2017) or ‘Industry 4.0’ (Brettel et al., 2014) promises substantive productivity gains by applying technologies such as sensors, RFID chips, robotics and machine learning to a vast range of manufacturing settings (Brynjolfsson and McAfee, 2014). These general-purpose technologies (Bresnahan, 2010) underpin a technological system (Perez, 2010) which may lead to profound change in regional economies, via shifts in industrial organisation, product and physical spaces (De Propris and Bailey, 2020). This creates new challenges for policymakers.

This paper makes two contributions to the field. First, much Industry 4.0 analysis focuses on *users* (Corò and Volpe, 2020). Instead, I look at *producers*: technology companies combining programming expertise with a physical product, or derived service. Such ‘hardware’ firms, in technology industry parlance, are under-explored in the Industry 4.0 literature – although tools that ‘connect the internet to the real world’, in the words of one of my interviewees, drive its underlying innovation and growth effects.

Second, I explore producers’ *regional location patterns and development pathways*, and their implications for policy. I develop a simple framework that sites Industry 4.0 producers as actors in a larger technological system (Freeman, 1991) *and* in physical space. While the technology systems literature has surprisingly little to say about space, in practice producers organise activity – prototyping, at-scale production and distribution – either inhouse, locally or in larger production networks (Gereffi et al., 2005; Yeung and Coe, 2015).

This framework then also tests whether key stylised facts in the broader technology industry also hold for hardware. Startups are held to be foundational for ‘tech’ innovation, of whom a successful few scale through VC funding or acquisition (Ewens et al., 2018). Such startups thrive in dense clusters (Saxenian, 1994; Hutton, 2008; Kerr and Robert-Nicoud, 2019) that shape a local entrepreneurial ecosystem.

These classical pathways may differ in the hardware space. Hardware startups 'produce physical goods yet lack the internal organisational machinery of firms' (Eisenburger et al., 2019). Product complexity and scale economies may advantage incumbents (Methé et al., 1996), pushing entrants to collaborate with them (Gans and Stern, 2003). Existing clusters may generate related entrepreneurship (Boschma and Frenken, 2011). But entrants' need for physical supply chains may lead to more dispersed production geographies (Sturgeon et al., 2008). And, to the extent that Industry 4.0 forms part of a national industrial strategy, state actors may play a larger role (Borrás and Edler, 2020).

I apply this framework to an exploratory case study of hardware startups and SMEs in the Stockholm metro region. Sweden – especially the Stockholm area – crystallises these broader questions. Stockholm is one of Europe's leading technology hubs, with thousands of small companies and global players such as Skype, Spotify, Mojang and Klarna (Semuels, 2017). In 2012, over 50% of *all* Sweden's tech workers were based in the Stockholm metro region (Giertz, 2015a). Sweden's industrial heritage – especially telecoms and electrical engineering MNEs – has shaped its technology scene (Chaminade et al., 2010; Gens et al., 2015). The State's tradition of activist industrial policy continues in programmes that aim to shift the country's manufacturing onto a more technology-intensive and sustainable trajectory, and strategies to promote new firm formation (Ketels, 2009). This reflects both a desire to update Sweden's industrial traditions, notably through 'innovation systems' agencies such as Vinnova (Grillitsch et al., 2019), and a response to the so-called 'Swedish Paradox' – high levels of R&D spending but low productivity (Bitard et al., 2008; Kander and Ejermo, 2009). The policy mix also includes a number of cluster initiatives (Lundequist and Power, 2002) notably the flagship Vinnova-led Vinnväxt regional programme (Nuur et al., 2009).

I draw on 27 semi-structured interviews in both startups and more established SMEs, plus interviews with policymakers and industry intermediaries. I uncover a growing milieu with much economic potential. Product complexity and a lack of informed investors make scaling very challenging. Notably, state support – via grants and loans – is as common as angel/seed/VC funding. Perhaps surprisingly, participants also report limited affordances of cluster location, with little learning from peers or MNEs. Instead, many connect to the national ecosystem at the early stages – via hiring, supply chains and prototyping / production partnerships – while volume manufacturing is offshored.

Overall, entrants are on slower, growth pathways than software-focused counterparts in the same region. In response, I suggest some additional national / regional policy interventions in the industrial policy tradition.

The paper contributes to the growing Industry 4.0 literature. The results additionally contribute to knowledge of industrial clusters, especially those in Sweden (Power and Jansson, 2004; Braunerhjelm, 2009; Nuur et al., 2009; Chaminade et al., 2010; Grillitsch et al., 2019) and to the growing literature on makers and makerspaces (Fassio and Grilli, 2016; Wolf-Powers et al., 2017; Eisenburger et al., 2019; Smith, 2019). The rest of the paper is organised as follows. Section 2 provides a framework; Section 3 outlines the Swedish case. Section 4 sets out the methodology. Section 5 gives findings. Section 6 concludes.

2 / Framework: placing Industry 4.0 startups

2.1 / From technologies to systems

'Industry 4.0' has no standardised definition. We can think of it as an evolving set of a) technologies, b) product/service applications and c) industry settings. Common technologies include sensors and radio chips, AI; machine learning; 3D printing; nanotech and cloud computing. Many have general purpose characteristics (Bresnahan, 2010) applicable to a vast range of settings (Brynjolfsson and McAfee, 2014). This includes automating existing activities (such as production lines) or products (such as medical devices) but also new or 'recombinant' use-cases (Kremer, 1993; Arthur, 2009), for example 'smart objects' (such as wearables or drones). These products require software and a range of related services, including leasing equipment, data analytics, consultancy and training (Vendrell-Herrero and Bustinza, 2020).

We can place these components in a larger, dynamic 'technological system' (Freeman, 1991; Perez, 2010): a set of technologies and its network of producers, suppliers, distributors and users. Such systems may benefit from (potentially substantial) internal spillovers (Kremer, 1993; Perez, 2010). A system's broader impacts depend on whether it involves essentially incremental innovation (Geels and Schot, 2007), or is a transition to a new paradigm (Dosi, 1982; Perez, 2010). The 'Fourth Industrial Revolution' nomenclature sometimes ascribed to Industry 4.0 reflects more aggressive claims of its impacts (De Propris and Bailey, 2020).

2.2 / Geographies of production

Despite their emphasis on multi-level frameworks, technology systems frameworks are notable for their lack of interest in space – specifically industrial clusters and larger production systems (Arthur, 2009). This is an important omission, given the roles physical proximity plays in knowledge spillovers, and thus in technology systems' evolution. While ICTs increasingly allow activity to be managed across space (Grabher and Ibert, 2014), for complex activities physical proximity remains valuable. Notably, much 'tech' activity organises into dense clusters, reflecting gains from input-sharing, firm-firm linkages, localised knowledge spillovers and signalling (Saxenian, 1994; Duranton and Puga, 2001; Romanelli and Khessina, 2005; Hutton, 2008; Kerr and Robert-Nicoud, 2019).

This calculus may differ for hardware startups, who need to develop prototypes, manufacturing and distribution systems. How these value chains (Gereffi et al., 2005) or production networks (Yeung and Coe, 2015) are organised is a key question for this paper, especially hardware firms' reliance on physical proximity versus partners at a distance (Mudambi, 2008). As suggested by evolutionary economic geographers (Boschma and Frenken, 2011) historic clusters in related activities can enable local entrepreneurship (Eisenburger et al., 2019). However, given low-cost technology (Varian, 2005) and under globalisation (Sturgeon et al., 2008), even startups can extend some workflows across space. Understanding production system geographies has important implications for regional policy(Wolf-Powers et al., 2017).

2.3 / Firm trajectories and strategy

The geographical issues link to broader questions of firm strategy. Recent decades have seen a vast increase in technology entrepreneurship, driven by – among other factors – ICTs that reduce company formation and running costs (Gans and Stern, 2003; Arthur, 2009; Ewens et al., 2018). These factors lower the minimum efficient scale for firms (Audretsch et al., 2018).

In the hardware space, it is less clear if entrants have the upper hand. Startups lack pre-existing commitments, enabling more 'disruptive' activity (King and Tucci, 2002; Faroughi and Stern, 2019). However, physical product complexity typically requires knowledge from multiple domains, alongside complementary assets such as production lines and distribution systems. Incumbents may have greater 'complementarities of experience' (Nerkar and Roberts, 2004) or absorptive capacity (Cohen and Levinthal, 1990). Incumbents may also be less credit-constrained in conducting R&D (Audretsch et al., 2018). Together, these factors may raise the minimum efficient scale for hardware to the point where incumbents have already captured most economies of scale. Studies of telecoms, computer hardware and digital medical devices provide some support for this (Methé et al., 1996; King and Tucci, 2002; Faroughi and Stern, 2019), although as Bayus and Argarwal (2007) show, incumbent advantage may erode over time.

Hardware startups may then choose to co-operate with incumbents. Gans and Stern (2003) highlight two factors influencing this choice: whether products can be easily appropriated, and the importance of complementary assets. Collaboration might involve joint ventures; looser networking/mentoring through industry groups; or input-sharing, allowing access to specialised equipment (Madaleno et al., 2018; Cohen et al., 2019). Venture capital firms have traditionally provided intermediary roles in software (Ewens et al., 2018); to the extent VC is less present in hardware, incumbent firms, universities and/or the State may be more important collaborators. In turn, this suggests a number of roles for national and regional policymakers.

3/ The Swedish context

Sweden – and the Stockholm region in particular – form a rich case study for these issues. Sweden has a deep history in information and communication technologies, especially electronic engineering, and related fields in advanced manufacturing

(Kander and Ejermo, 2009; Giertz, 2015b; Gens et al., 2015; Ketels, 2009). Having industrialised relatively late, Sweden developed rapidly through corporatist policy frameworks (Haug, 2004). A key policy was the 'development couples' strategy (Gens et al., 2015), in which the state would act as the anchor client for a private sector firm developing some technology of national importance. This was particularly successful in mobile communications, helping establish Ericsson as both the country's largest ICT firm and a global player. However, the early 2000s saw the firm enter crisis, driven by the dotcom crash and strategic miscalculations, laying off half its workforce by 2004, and gradually shifting from hardware to ICT services. In line with evolutionary cluster frameworks (Chaminade et al., 2010; Boschma and Frenken, 2011), many laid-off engineers moved into related consultancy or set up their own businesses in the region. This wave of entrepreneurial activity was reinforced by other factors. Sweden entered a deep economic crisis in the early 1990s (see Freeman et al (1997)) and took an increasingly deregulated approach afterwards (Bitard et al., 2008; Chaminade et al., 2010; Giertz, 2015b). In 1995 the country joined the then European Community, with State Aid rules putting limits on industrial strategy. The 'Swedish Paradox' – high R&D spending but low productivity (Bitard et al., 2008; Kander and Ejermo, 2009) – led to further reforms, especially to tax and competition policy (Semuels, 2017).

Today, 'hardware' has an outsize role in the Swedish national innovation system (Chaminade et al., 2010). Fassio and Nathan (2020) show that STEM-intensive sectors[1] employed over 2/3 of all Swedish STEM workers and covered over three quarters of all patenting during 2007-2012. Giertz et al (2015a) find that 'hardware components' and 'complete systems' verticals comprised 14% of firms and over 20% of all ICT sector staff in 2011, with a smaller set of around 360 'R&D focused consulting' firms. The complete systems vertical is dominated by a few large incumbents, of which Ericsson accounted for over 70% of all employees. The hardware components vertical is dominated by SMEs, with around 10 employees on average.

Industry 4.0 production is also highly clustered, especially in the Stockholm region. Its ICT industries grew rapidly during the 1990s, paralleling the fortunes of Ericsson, and attracting MNEs such as Infosys, Huawei and Lenovo close to the firm's HQ at Kista,

[1] STEM-intensity for an industry is defined by its share of workers in STEM occupations.

around 12km North of central Stockholm (Ketels, 2009). The cluster also diversified, into activities such as ICT services and software consulting (Lundmark and Power, 2008): these auxiliary industries expanded during Ericsson's subsequent contraction. Stockholm is today one of Europe's largest technology clusters (Lundmark and Power, 2008), with strengths in software, fintech and music technology (Power and Jansson, 2004; Braunerhjelm, 2009). However, local hardware activity is dominated by large firms – Stockholm county comprises 47% of all STEM-intensive employment, but only 25% of all STEM-intensive firms (Nathan and Fassio, 2020), especially the MNE-dominated 'complete systems' segment identified by Giertz et al (2015a).[2] By contrast, hardware components and R&D consulting activities are more dispersed across the country. Given this, a key issue for local hardware startups is then whether they make links to the local, as opposed to the national, innovation system.

4/ Research design

I develop an exploratory case study of Industry 4.0 production in the Stockholm county area. Sweden and Stockholm are a paradigmatic case study to explore these issues (Flyvbjerg, 2006). I use semi-structured interviews, a method that is particularly appropriate for capturing emergent economic phenomena (Schoenberger, 1991). This design follows tech cluster case studies by Hutton (2008) and Nathan and Vandore (2014) as well as Power and Lundquist's (2004) study of Stockholm 'music tech', and studies of Maker firms by Smith (2019) and Eisenburger et al (2019). Clark (1998) highlights risks in such 'close dialogue' with corporate actors. To mitigate these I deploy a pre-existing conceptual framework, refined through interviews, rather than grounded theory; and use public information on platforms such as LinkedIn and Crunchbase to generate prior descriptives.

Concretely, my work with firms draws on three sampling frames. The first is a hardware-focused incubator space in central Stockholm: members are typically under five years old and with less than 10 staff (hence COWORKING). All tenants were

[2] Swedish administrative geography comprises 290 municipalities and 20 counties. Stockholm County comprises 26 municipalities.

contacted, yielding 11 interviews, a response rate of 39%. The second is a business membership network of around 80 hardware firms, typically more established companies with workforces of 10-100. In this case, the sample was restricted to 30 firms based in Stockholm county or with significant presence in the area, as indicated by plant location (hence CITY). Companies were contacted in waves, yielding five interviews, a response rate of 17%. Third, other stakeholder interviews were snowballed and included policymakers (national agencies, local government) and industry intermediaries (university commercialisation offices, industry networks/platforms and co-working space managers). All interviews were recorded during 2017 and 2018. Firm transcriptions were open coded by hand, then validated using topics generated through feature extraction and topic modelling. [3] Policy/stakeholder interviews were open coded by hand. In what follows firm interviews are prefixed F, policymakers P, industry intermediaries I.

5/ Findings

5.1 / Firms and founders

Interviews confirmed the breadth of the hardware 'space' (Nerkar and Roberts, 2004), and the larger minimum efficient scale this implies for entrants (Audretsch et al., 2018). First, reflecting the fuzziness of 'Industry 4.0' terminology (De Propris and Bailey, 2020), interviewees variously defined themselves in terms of technologies, applications and industry spaces. Notably, none identified as 'Industry 4.0', suggesting this is policymaker rather than industry terminology. Specific answers included one or more of Internet of Things (4/16); consumer electronics (3); wearables (2); software (2), SaaS (2); consulting (2); and one each of drones; AI; medical/ tech; human-computer interaction; geolocation; radio; cloud. Second, the core 'product' was complex. For example, each firm whose primary product was physical, also built software and/or apps. The majority involved recombinant innovation (Kremer, 1993):

[3] Text analysis and topic modelling using quanteda (Benoit, 2018) and stm (Roberts et al, 2016). Coding and analysis in Dedoose.

F8: [Product P] has been there for maybe 15 or 20 years now, or more. … What are new are the adaptations that are being applied onto it … so in that sense, this is a new product.

Over a quarter (5/16) had developed general purpose technologies applications (Bresnahan, 2010). For example, one firm was exploring applications of its transmitter in a person-overboard system in luxury yachts; elder care; pet health monitoring; and stolen vehicle tracking (section 5.5). A minority in both groups had embraced a servitisation business model.

Third, complexity was reflected in team size and growth. All but one firm [F14] had two or more founders, often adding further senior roles / co-founders early on. Typically a business person was brought in after technical development: in line with Cohen and Levinthal (1990) industry observers emphasised that researcher-led teams often need a CEO with manufacturing business experience [I24]: *'you need more than one brain'* to do hardware [I26]. Consistent with this, founders in the younger COWORKING group 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 CITY firms, founders / senior employees usually identified as *'business people'*, some with engineering backgrounds; all had over 10 years' relevant industry experience. Notably, only CITY interviewees spanned business, engineering and ICT worlds:

F13: So, so my whole career, plus 30 years something, has been… I can say that I'm business oriented, product oriented, but I have a rather high… I am an engineer, from start, and I like tech things, so in that regard I think I am… I have spent all of my career in this space, so I guess I like it. (Laughs)

5.2 / Industrial legacy

The majority of firms sited themselves in a larger tradition of Swedish electronic engineering and hardware expertise; that is, as part of a national innovation system (Chaminade et al., 2010) *and* as part of a technology system (Freeman, 1991).

However, none presented their activities as a radical, revolutionary break (Perez, 2010); rather, the majority argued that their products extended this national industrial history:

> *F13: The companies in Sweden, and things like that – companies like energy companies; the ABBs, Ericssons, Nokias of the world – they are coming from radio, from hardware, from electronics…Even though Ericsson today is more of a gigantic software house, they have their roots in hardware, and still there is tradition in hardware.*

Especially in the COWORKING group, respondents drew direct geographical connections, citing growing up around these prominent national champions, taking pride in this and wanting to honour it. This sense of evolutionary branching (Boschma and Frenken, 2011) is in line with Eisenburger et al (2019)'s notion of localised 'industrial inheritances':

> *F9: … there is a tradition that people were… I mean, there's a lot of our parents, actually not mine, but many of the parents here who have probably worked with Ericsson or related or engineering. Of course we were quite big in engineering, we have been that historically.*

However, interviewees had notably few concrete links to MNEs in the region (Sections 5.3 and 5.4). Policy and industry stakeholders also had more mixed views. Some stressed the importance of history and path-dependence [I21, I22, I23, I24, P18, P19], and were positive about the role of incumbents. Others complained that *'Sweden hasn't established any new industries since the 1950s'* [I26] and saw Industry 4.0 as a lever of change on the country's advanced manufacturing MNEs [I25, I26].

5.3 / Geographies of production

How far did firms plug into these industrial legacies? The interviews uncovered two distinct geographies. First, the organisation of 'HQ functions' –founding teams and direct employees – closely resembled the wider tech industry; but with notably less interest in localised interaction, even in shared workspaces. Second, manufacturing geographies varied hugely, especially with the firm's developmental stage. Analogous to startups in big ‘nursery cities’ (Duranton and Puga, 2001), firms used Swedish partners in prototyping and short run production, before offshoring to cheaper locations for volume activity. Notably, Swedish intermediaries often played brokering roles.

Per other tech startups (Hutton, 2008; Kerr and Robert-Nicoud, 2019), ‘HQ’ functions involved a mix of close co-location and remote working enabled by low-cost technology. Notably, while the majority had single sites (6/11 COWORKING, 2/5 CITY), multi-plant COWORKING firms were *more* physically dispersed than the larger, older CITY firms, with 3/5 ‘micro-multinationals’ (Varian, 2005). To manage these functions, firms combined communication technologies and face to face contact, even when co-located (Grabher and Ibert, 2014; Martins, 2015):

> *Interviewer: And have you physically met everyone in the team or are there people who you’ve just met online?*
> *F11: One I haven’t met physically yet. But she is still very early in the process. … we had 12 meetings, of which 10 were online and two IRL.*

The split was often carefully calibrated to roles, or built around key individuals:

> *F12: ... in sales and product management, we have an urge to go to meet people ... but I would say most of our tech guys, they’re much more comfortable with interaction in Slack, textual, more exact interaction. But still you need to develop the interpersonal trust and… it’s being mediated by the people that actually go there … and tell the developers that these guys are all right.*

Only one company [F16] had reshored activity – specifically, their software developers – because this had come to be seen as a core activity.

All but two interviewees used shared offices. COWORKING was an incubator run jointly by a national accelerator programme and one of the city’s universities. Many of the tenants were accelerator graduates. As with many other such spaces, (Madaleno et al., 2018; Cohen et al., 2019), COWORKING provided a peer group and industry access, especially to Swedish MNEs, through events and networking. Industry interviewees [I23, I26] felt this latter was the space’s main advantage. Tenants had more mixed views. In the main, tenants placed greater emphasis on low cost [4/11], university location [4/11] and access to the space's specialised equipment [6/11], in line with other studies on Makerspaces (Fassio and Grilli, 2016; Wolf-Powers et al., 2017; Smith, 2019). While some [4/11] welcomed networking and visibility, others disliked interaction or felt the priority was to build the firm. This inability or unwillingness to plug in parallels interviewees' views of the wider Stockholm cluster (see Section 5.3):

> *F2: but it's like, you have a lot to do.*

> *F10: I am very bad at [networking] which is like why the community manager has been yelling at me.*

Along similar lines, CITY firms looked for 'professional' co-working spaces offering flexible accommodation for growing teams [F12, F16]. One [F12] had co-located with a production partner, but placed little emphasis on interaction with others in the building [F12].

By contrast, production geographies were variable, reflecting both cost / quality tradeoffs as firms scaled (Eisenburger et al., 2019; Wolf-Powers et al., 2017) and broader challenges in managing distant activity (Mudambi, 2008; Sturgeon et al., 2008). 5/16 firms, all but one in the younger COWORKING group, kept production activity in-house; of these one had a technology partner abroad, and another was planning to move manufacturing to a Baltic country. Of the remainder, two kept manufacturing in Sweden; eight had offshored it; one did both.

Strikingly, more had production partners in Sweden than in Stockholm, suggesting that the national innovation system was more important than the local / regional ecosystem. This is consistent with both the broader distribution of Industry 4.0 producers and consultants across the country (Section 3) and many firms' view of the Stockholm cluster (Section 5.4).

Firms keeping manufacturing in Sweden cited the desire to use specialists, and a business model majoring on quality; or the need for small / fast runs. For the rest, Swedish partners were used predominantly for product development, prototyping and small-scale production:

> *F14: And then [our founder] just started to ... gather the technical team. And Stockholm was the right place to do it because there are a lot of telecoms companies – from Nokia, to Ericsson and so on.*

The more generic the activity and/or the bigger the volume, the more likely supply was offshored: 4/5 CITY firms used international supply chains, while only 4/11 COWORKING firms did so. Interviewees used well-established global production networks (Yeung and Coe, 2015) – typically the Baltic states or East Asian countries. The main reasons given were capacity and cost-based:

> *F7: ... when I started off, I started visiting several Swedish electronics manufacturing companies and when I was doing the calculations, the minimum retail price ... that's too much. ... [and] it was hard to get a meeting ... when I sent a mail to the largest manufacturer in the world of [X products] and asked them, "Could you make an alteration to an [X] because we have a patent…" And less than 24 hours later, I got a 3D drawing back.*

Industry stakeholders [I22, I23, I24, I26] emphasised that for startups, developing these supply chains was expensive and risky, involving substantial 'complementarities of experience' (Nerkar and Roberts, 2004). Notably, some interviewees sought out Swedish actors who could offer rich advice on contract design, minimum standards and project management *outside* Sweden. One [F11] used a Chinese factory – founded by an expat former Swedish factory owner. Another [F16] used a Swedish broker to arrange contracts with East Asian manufacturers.

5.4/ The Stockholm ecosystem

Stockholm was commonly described as the engine of the national economy, with a critical mass of economic activity, industrial legacy plus supportive institutions, that firms could draw on. Nevertheless, hardware startups faced substantive constraints in doing so.

Interviewees agreed that the city / metro area was in a growth spurt – *'Stockholm is exploding with startups at the moment'* [I24] with more firms and angel/VC finance, especially from the US, arriving in the last five years. The popularity of entrepreneurship as a lifestyle choice had helped drive this [I24]. Stakeholders also characterised a shift to *'growth and maturity'* [I23], with major local players – such as Spotify, Mojang and King – now over 10 years old. With parallels to the Ericcsson legacy (Section 3), former employees had established their own firms, or shared experience in meetups or advisory roles, spreading knowledge and experience across the cluster. Some were optimistic these dyanmics also helped hardware firms. iZettle, a card reader firm, showed that hardware firms could break through [I24]; there was also a *'pendulum swing'* to hardware, as founders recognised the potential to leverage Swedish expertise [F13].

In theory, Stockholm hardware startups should benefit from this localised industrial legacy and from their 'intercluster' position, which should allow Jacobian spillovers (Power and Jansson, 2004). In practice, firms' experience was mixed. Interviewees emphasised that Stockholm provided important input-sharing and supplier/partner opportunities. In part this was through Ericsson's legacy:

> *F16: ... the reason I think it's good for us here is that you have in Sweden the legacy of Ericsson, right… What that has created is… a whole raft of smaller technology companies that contract back to Ericsson ... They have a high level of competence, and there's also a lot of contract engineers floating around who have a high level of competence.*

Academia, especially KTH, Stockholm University and the Karolinska Institute, also played multiple roles. COWORKING firms had close links with the host university (some founders were ex-students, one was a current student). The university also supplied employees and interns, equipment, and business support. CITY firms had less interaction with Stockholm's universities, except through hiring graduates of those institutions.

Overall, only two interviewees mentioned Kista, and only one [F10] had direct contact with locally-based MNEs. Similarly, many companies were sceptical about local networking and learning from other SMEs. One criticism was that meetups generally involved early-stage ‘noisy learning’ (Kerr et al., 2014), not substantive product development:

> *F14: Yeah, there is Stockholm tech monthly meet-up … But apart from that there’s no special thing, gathering, for start-ups that are at a later stage. … There are some, I don’t know, awards – like mobile awards or Nordic start-up awards … But unless you are winning, you’re not going usually. (Laughs)*

Interviewees also distanced themselves from ‘lifestyle entrepreneurs’ who they felt now dominated the milieu. Echoing many COWORKING tenants’ view of networking (section 5.3), they presented as more serious than ‘softer’ ventures:

> *F1: We learnt more in two weeks in Palo Alto than two years in Sweden.*

> *F10: There is like this hip thing of being an entrepreneur and having a start-up etc. Doing much talking, attending many events. (Laughter) …. We consider ourselves to be very anti- those things …*

> *F15: 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.*

5.5 / Firm trajectories

The vast majority of firms sought to scale (Gans and Stern, 2003; Kerr et al., 2014): in this they faced various challenges, some generic to tech startups (Nathan and Vandore, 2014; Kerr and Robert-Nicoud, 2019), others specific to hardware.

Key generic challenges were market access and recruitment. Respondents were keen to export, especially to large EU and North American markets. COWORKING firms typically focused on selling in Baltic / Nordic countries first; CITY firms were focused on Europe and/or the US. One issue (flagged by 6/16 firms) was that Sweden was simply too small in population terms. The other issue was a paradox: as a pro-technology country (Section 3), Sweden offered an excellent test market, but with huge competition for customer attention:

> *F11: Everything that's new and on the verge of becoming the next thing, we already have it in Sweden.*

> *F14: Everyone is into tech, everyone understands tech. Initially, from our point of view, we looked at this as an advantage. But then we realised that actually our market in Sweden, even if it's a test market, it's really small.*

A further issue was recruitment, where as expected, small, young firms found it hard to find and attract people with technical skills This was particularly difficult in Stockholm, given the huge demand for coders, engineers and other IT staff (7/16). 3/16 firms also mentioned high housing costs, especially for foreign staff:

> *F2: We have an employee in Norway, actually. He's a developer, he develops from there ... the plan is for him to come here. But there's the housing, Stockholm is difficult.*

Other challenges were hardware-specific. For the 5/16 firms with general purpose technologies (Bresnahan, 2010), the range of potential applications, versus these firms' small size and the need for revenue, had forced a focus on a single product or small set where they saw immediate demand:

> *F2: It's a very, very broad palette of applications. That doesn't mean we need to, we can focus on every, each and every vertical, right? ... That's partly what the beta tests are for ... choose a segment, choose a vertical to focus on. And then, you scale it up, you conquer that vertical and then you take the next one.*

F16: You can't use the shotgun approach forever. ... You know, we're focusing on what we perceive as the lowest hanging fruit here, because like every start-up we need to get into the market and start earning revenue.

Others [F8, F10, F14] had pivoted because of IP issues or the presence of incumbents, as per Gans and Stern (2003). Notably, one only firm [F14] was actively seeking a joint venture with an MNE incumbent.

Interviewer: So you'd already decided to switch from consumer to industrial. What was the thinking there?
F8: That's a good question ... as much as it was a boom, I felt it was not sustainable ... anything that's consumer, especially if it's hardware based or hardware centric, to a great deal, can be easily copied by Asian manufacturers and there's not much protection that we can have for that. ... and then we don't have the economy of scale as much as they have there ....

Raising money also presented particular challenges. Most used a portfolio of tools, but three features stood out. First, unlike software, where firms typically draw on seed / angel / venture finance for a long pre-revenue period (Kerr et al., 2014; Ewens et al., 2018), here public sector grants and loans [6/16] were as common as angel/VC [4/16] and seed funding [3/16] combined. While one suggested this was a temporary phase [F2], most respondents flagged investors' lack of knowledge of hardware, apart from perceptions of complexity and risk:

F8: There's a lot of good VCs around here in Stockholm ... but I don't know if they're relevant to us ... They're not in touch with our markets, and I don't know if they would relate to the technologies we develop.

Industry stakeholders agreed, suggesting that private sector VC firms were *'a bit scared of hardware'* [I26]. Notably given the industrial history, no 100% hardware-focused VC firms operated in Sweden [I23]. Instead, the national state – especially the ALMI agency – had stepped in through grants and loan finance. In some cases public money had also funded the basic research behind the company: 4/16 firms were university spinoffs or built from academic research.

Second, the lack of outside finance had pushed a number of companies towards revenue-based growth (5/16), even including very young startups in the COWORKING group (2/5). Third, firms combined these strategies with more innovative tools to raise money and profile at the same time: 3/16 had expanded by winning innovation prizes; all the consumer-facing firms used Kickstarter, which was also seen as a useful market-testing device:

> *F15: For me it was two things. It was of course to raise some capital …, but I also had the idea if we can't make… if the Kickstarter community won't buy into it, I mean nobody will. I mean, it's an early adopter environment.*

6/ Discussion

The growing Industry 4.0 literature (De Propris and Bailey, 2020) has so far had little to say about producers, especially startups and SMEs, or about those firms' embeddings into regional and larger production systems (Corò and Volpe, 2020). I develop a simple framework siting Industry 4.0 producers as actors in a larger technological system (Freeman, 1991), making decisions about production geography and strategy. While the technology entrepreneurship literature emphasises the importance of dense clusters, angel/VC finance and acquisitions/IPOs (Saxenian, 1994; Ewens et al., 2018 ; Kerr and Robert-Nicoud, 2019), product complexity, a high minimum efficient scale, the presence of incumbents and state intervention may lead to different outcomes for hardware startups.

I explore these issues in the Stockholm hardware cluster, a case crystallising these larger issues. The milieu is closely linked to the country's history of electrical engineering, with clustering of large players, especially Ericsson, in the Stockholm metro area (Chaminade et al., 2010; Giertz, 2015b) as well as policy efforts to promote entrepreneurship and US-style startup culture (Ketels, 2009).

Theory suggests that technological systems, such as Industry 4.0, have potentially huge spillovers (Brynjolfsson and McAfee, 2014), especially if they represent revolutionary rather than incremental change (Perez, 2010). Here, most firms placed themselves within a continuous industrial tradition rather than presenting as disruptors – a view not shared by policy or industry stakeholders. The breadth and complexity of hardware activities also suggests that for *individual protagonists*, especially SMEs, there are substantial opportunity costs in accessing externalities: many interviewees emphasised firm-building over networking, both in co-working spaces and the wider Stockholm cluster.

While the geography of 'HQ functions' closely resembled those of other tech startups, firms organised manufacturing at multiple scales, drawing on Swedish expertise largely for prototyping and small-scale production phases. Strikingly, given their location in one of Europe's largest tech clusters, production partners were as likely to be drawn from across the country as from the Stockholm area. In contrast to other urban tech clusters (Power and Jansson, 2004; Hutton, 2008; Nathan and Vandore, 2014; Martins, 2015), while protagonists benefited from localised input-sharing and matching, especially access to Stockholm's skilled labour force and specialist equipment, but rather less from peer learning or contacts with MNEs.

Respondents faced three structural obstacles in taking small-run, complex products and services to scale. First, technological complexity require bigger founding teams and longer development time. Second, physical products generate additional challenges and risks around (inter alia) scaling up production, logistics, standards and certification (Eisenburger et al., 2019; Wolf-Powers et al., 2017). A third issue is a finance Catch-22: investors see hardware as requiring more resources, but generating slower/riskier returns; fewer firms scale; fewer proceeds are ploughed back into new hardware startups, and fewer successful founders apply their knowledge to help new businesses in the space. As a result, hardware startups were typically on slower growth trajectories than (say) software-focused counterparts, with most growing through revenue or public grants/loans.

Overall, these challenges suggest substantive structural obstacles in applying classical startup/cluster approaches to advanced manufacturing settings. However, these market and co-ordination failures also present a number of potential roles for policymakers. Endogenous growth frameworks and innovation systems frameworks (Freeman, 1991) both emphasise the role of the public sector in co-creating innovative activity (Borrás and Edler, 2020). State actors were already supporting a number of interviewees through basic research or downstream grants and loans. The striking lack of interaction between startups and local MNEs represents another potential site for policy. Sweden's dominant electrical engineering firms have tended to focus on incremental innovation rather than disrupting core business models [I22, I25]. Firms have also been used to owning and controlling IP, complicating joint ventures [I26]. Nevertheless, there were encouraging signs of local policy innovation. These included many-to-many industry networks that linked MNEs and SMEs; corporate accelerators; and network-focused co-working spaces. These initiatives could form the basis for further interventions, linking incumbents, with financial resources and the ability to leverage economies of scale, and smaller / younger firms on the technological frontier.

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References

Arthur WB (2009) *The Nature of Technology.* London Penguin.

Audretsch D, Hafenstein M, Kritikos AS, et al. (2018) Firm Size and Innovation in the Service Sector. Reportno. Report Number|, Date. Place Published|: Institution|.

Bayus BL and Agarwal R (2007) The Role of Pre-Entry Experience, Entry Timing, and Product Technology Strategies in Explaining Firm Survival. *Management Science* 53(12): 1887-1902.

Bitard P, Edquist C and Hommen L (2008) Reconsidering the paradox of high R&D input and low innovation: Sweden. In: Edquist C and Hommen L (eds) *Small country innovation systems: globalization, change and policy in Asia and Europe*. Cheltenham: Edward Elgar, pp.237-280.

Borrás S and Edler J (2020) The roles of the state in the governance of socio-technical systems' transformation. *Research Policy* 49(5): 103971.

Boschma R and Frenken K (2011) The emerging empirics of evolutionary economic geography. *Journal of Economic Geography* 11(2): 295-307.

Braunerhjelm P (2009) The Genesis and Evolution of the Stockholm Music Cluster. In: Karlsson C, Andersson A, Cheshire P, et al. (eds) *New Directions in Regional Economic Development. Advances in Spatial Science*. Berlin: Springer.

Bresnahan T (2010) General Purpose Technologies. In: Hall B, H. and Rosenberg N (eds) *Handbook of the Economics of Innovation*. North-Holland, pp.761-791.

Brettel M, Friederichsen N, Keller M, et al. (2014) How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 Perspective. *International Journal of Mechanical, Industrial Science and Engineering* 8(1): 37-44.

Brynjolfsson E and McAfee (2014) *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies.* New York: W. W. Norton & Company.

Chaminade C, Zabala J and Treccani A (2010) The Swedish national innovation system and its relevance for the emergence of global innovation networks. Reportno. Report Number|, Date. Place Published|: Institution|.

Clark GL (1998) Stylized Facts and Close Dialogue: Methodology in Economic Geography. *Annals of the Association of American Geographers* 88(1): 73-87.

Cohen S, Fehder DC, Hochberg YV, et al. (2019) The design of startup accelerators. *Research Policy* 48(7): 1781-1797.

Cohen WM and Levinthal DA (1990) Absorptive Capacity: A New Perspective on Learning and Innovation. *Administrative Science Quarterly* 35(1): 128-152.

Corò G and Volpe M (2020) Driving factors in the adoption of Industry 4.0 technologies In: De Propris L and Bailey D (eds) *Industry 4.0 and Regional Transformations*. Oxford: Routledge

De Propris L and Bailey D (2020) Disruptive Industry 4.0+. In: De Propris L and Bailey D (eds) *Industry 4.0 and Regional Transformations*. Oxford: Routledge.

Dosi G (1982) Technological Paradigms and Technological Trajectories. *Research Policy* 2(47-62).

Duranton G and Puga D (2001) Nursery Cities: Urban Diversity, Process Innovation and the Life Cycle of Products. *American Economic Review* 91(5): 1454-1477.

Eisenburger M, Doussard M, Wolf-Powers L, et al. (2019) Industrial inheritances: Makers, relatedness and materiality in New York and Chicago. *Regional Studies* 53(11): 1625-1635.
Ewens M, Nanda R and Rhodes-Kropf M (2018) Cost Of Experimentation And The Evolution Of Venture Capital. Reportno. Report Number|, Date. Place Published|: Institution|.
Faroughi C and Stern AD (2019) Who Drives Digital Innovation? Evidence from the U.S. Medical Device Industry. Reportno. Report Number|, Date. Place Published|: Institution|.
Fassio C and Grilli L (2016) From technological to symbolic innovation? Open source, Maker Movement and global demand for 3D printers Reportno. Report Number|, Date. Place Published|: Institution|.
Flyvbjerg B (2006) Five Misunderstandings About Case-Study Research. *Qualitative Inquiry* 12(2): 219-245.
Freeman C (1991) Networks of innovators: A synthesis of research issues. *Research Policy* 20(5): 499-514.
Freeman RB, Topel R and Swedenborg B (1997) The Welfare State in Transition: Reforming the Swedish Model. *NBER Conference report* Chicago and London: University of Chicago Press.
Gans JS and Stern S (2003) The product market and the market for “ideas”: commercialization strategies for technology entrepreneurs. *Research Policy* 32(2): 333-350.
Geels FW and Schot J (2007) Typology of sociotechnical transition pathways. *Research Policy* 36(3): 399-417.
Gens M, Giertz E and Rickne A (2015) ICT related technology shifts in the engineering sector. In: Giertz E, Rickne A and Rouvinen P (eds) *Small and beautiful: The ICT success of Finland & Sweden*. Stockholm: Vinnova.
Gereffi G, Humphrey J and Sturgeon T (2005) The governance of global value chains. *Review of International Political Economy* 12(1): 78-104.
Giertz E (2015a) The Swedish ICT sector today. In: Giertz E, Rickne A and Rouvinen P (eds) *Small and beautiful: The ICT success of Finland & Sweden*. Stockholm: Vinnova.
Giertz E (2015b) Understanding the Swedish saga through an historical exposé. In: Giertz E, Rickne A and Rouvinen P (eds) *Small and beautiful: The ICT success of Finland & Sweden*. Stockholm: Vinnova.
Grabher G and Ibert O (2014) Distance as asset? Knowledge collaboration in hybrid virtual communities. *Journal of Economic Geography* 14(1): 97-123.
Grillitsch M, Hansen T, Coenen L, et al. (2019) Innovation policy for system-wide transformation: The case of strategic innovation programmes (SIPs) in Sweden. *Research Policy* 48(4): 1048-1061.
Haug R (2004) The history of industrial democracy in Sweden: Industrial revolution to 1980. *International Journal of Management* 21(1): 7-15.
Hutton T (2008) *The New Economy of the Inner City: Restructuring, regeneration and dislocation in the twenty-first century metropolis.* Abingdon: Routledge.
Kander A and Ejermo O (2009) The Swedish paradox revisited. In: Karlsson C, Johannesson B and Stough R (eds) *Entrepreneurship and Innovation in Functional Regions*. Cheltenham: Edward Elgar.
Kerr W, Nanda R and Rhodes-Kropf M (2014) Entrepreneurship as Experimentation. *Journal of Economic Perspectives* 28(3): 25-48.

Kerr W and Robert-Nicoud F (2019) Tech Clusters Reportno. Report Number|, Date. Place Published|: Institution|.
Ketels C (2009) Clusters, Cluster Policy, and Swedish Competitiveness in the Global Economy. Reportno. Report Number|, Date. Place Published|: Institution|.
King AA and Tucci CL (2002) Incumbent Entry into New Market Niches: The Role of Experience and Managerial Choice in the Creation of Dynamic Capabilities. *Management Science* 48(2): 171-186.
Kremer M (1993) The O-Ring Theory of Economic Development*. *The Quarterly Journal of Economics* 108(3): 551-575.
Lundequist P and Power D (2002) Putting Porter into practice? Practices of regional cluster building: evidence from Sweden. *European Planning Studies* 10(6): 685-704.
Lundmark M and Power D (2008) Labour market dynamics and the development of the ICT cluster in the Stockholm region In: Karlsson C (ed) *Handbook of Research on Innovation and Clusters: Cases and Policies*. Cheltenham: Edward Elgar.
Madaleno M, Nathan M, Overman H, et al. (2018) Incubators, Accelerators and Regional Economic Development Reportno. Report Number|, Date. Place Published|: Institution|.
Martins J (2015) The Extended Workplace in a Creative Cluster: Exploring Space(s) of Digital Work in Silicon Roundabout. *Journal of Urban Design* 20(1): 25–145.
Methé D, Swaminathan A and Mitchell W (1996) The Underemphasized Role of Established Firms as the Sources of Major Innovations. *Industrial and Corporate Change* 5(4): 1181-.
Mudambi R (2008) Location, control and innovation in knowledge-intensive industries. *Journal of Economic Geography* 8(5): 699-725.
Nathan M and Fassio C (2020) Exploring Industry 4.0 Production in Sweden. In: De Propris L and Bailey D (eds) *Industry 4.0 and Regional Transformations*. Oxford: Routledge, pp.133-151.
Nathan M and Vandore E (2014) Here be startups: exploring London's 'Tech City' digital cluster. *Environment and Planning A* 46(10): 2283-2299.
Nerkar A and Roberts PW (2004) Technological and product-market experience and the success of new product introductions in the pharmaceutical industry. *Strategic Management Journal* 25(8-9): 779-799.
Nuur C, Gustavsson L and Laestadius S (2009) Promoting Regional Innovation Systems in a Global Context. *Industry and Innovation* 16(1): 123-139.
OECD (2017) The Next Production Revolution. Reportno. Report Number|, Date. Place Published|: Institution|.
Perez C (2010) Technological revolutions and techno-economic paradigms. *Cambridge Journal of Economics* 34: 185-202.
Power D and Jansson J (2004) The emergence of a post-industrial music economy? Music and ICT synergies in Stockholm, Sweden. *Geoforum* 35(4): 425-439.
Romanelli E and Khessina OM (2005) Regional Industrial Identity: Cluster Configurations and Economic Development. *Organization Science* 16(4): 344-358.
Saxenian A-L (1994) *Regional Advantage: Culture and Competition in Silicon Valley and Route 128* Cambridge, MA: Harvard University Press.

Schoenberger E (1991) THE CORPORATE INTERVIEW AS A RESEARCH METHOD IN ECONOMIC GEOGRAPHY. *The Professional Geographer* 43(2): 180-189.
Schwab K (2017) *The fourth industrial revolution.* London: Crown Business.
Semuels A (2017) Why Does Sweden Have So Many Start-Ups? *The Atlantic*, 28 September 2017.
Smith TSJ (2019) 'Stand back and watch us': Post-capitalist practices in the maker movement. *Environment and Planning A: Economy and Space* 52(3): 593-610
Sturgeon T, Van Biesebroeck J and Gereffi G (2008) Value chains, networks and clusters: reframing the global automotive industry. *Journal of Economic Geography* 8(3): 297-321.
Varian H (2005) Technology Levels the Business Playing Field. *New York Times*, 25 August.
Vendrell-Herrero F and Bustinza OF (2020) Servitization in Europe. In: De Propris L and Bailey D (eds) *Industry 4.0 and Regional Transformations*. Oxford: Routledge.
Wolf-Powers L, Doussard M, Schrock G, et al. (2017) The Maker Movement and Urban Economic Development. *Journal of the American Planning Association* 83(4): 365-376.
Yeung HW-c and Coe NM (2015) Toward a Dynamic Theory of Global Production Networks. *Economic Geography* 91(1): 29-58.